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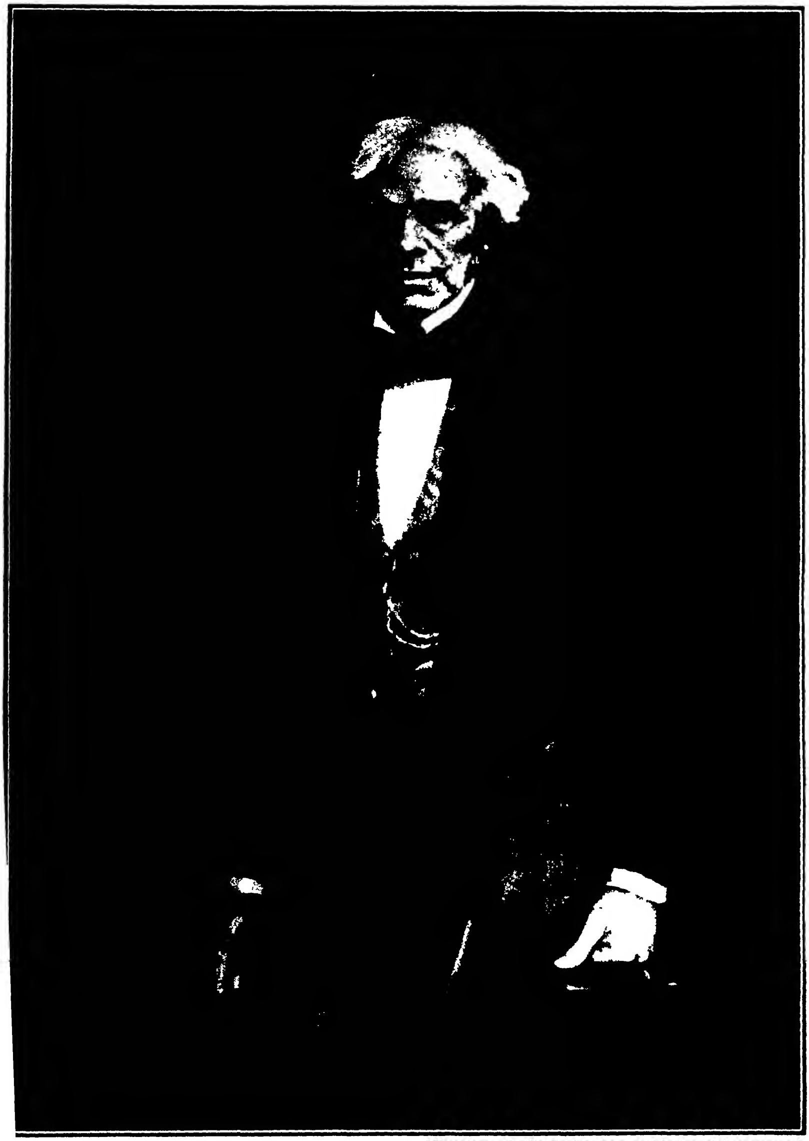
THE QUEST FOR POWER



(*Courtesy of The Institution of Electrical Engineers.*)

MICHAEL FARADAY, 1791—1867.

From the portrait painted by G. Harcourt, R.A., presented to the Institution of Electrical Engineers by S. Evershed, 1926.

[*Frontispiece.*

THE
QUEST FOR POWER
From Prehistoric Times to the Present Day

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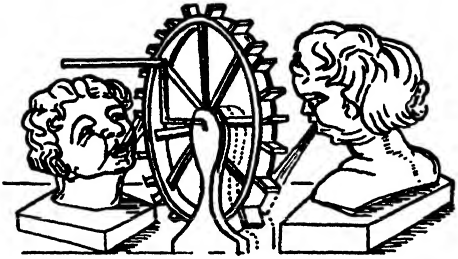

Kircher's Steam Wheel, 1656.

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IN FRIENDSHIP'S NAME
TO
HUBERT CECIL BOOTH,
F.C.G.I., M.INST.C.E.

WHO BY THE INVENTION AND SUBSEQUENT DEVELOPMENT OF THE VACUUM CLEANER HAS CREATED A NEW INDUSTRY, LIGHTENED THE BURDEN OF HUMAN TOIL, AND INCREASED THE HEALTH AND HAPPINESS OF INNUMERABLE HOMES

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INTRODUCTION

This book attempts to record the story of what is, perhaps, man's greatest adventure. It is written primarily for the intelligent general reader, and for the specialist in one branch of engineering who may be the general reader in another. Our object in writing it was to give a simple and connected account of man's endeavour through the ages to augment his own bodily power.

From the flint tools, the discovery of fire and metals, and other developments of prehistoric times, our story passes in its early chapters to some of the structural, transport, and allied achievements of ancient Egypt, Babylonia, Assyria, Greece, and Rome, with an occasional glance at similar developments in India and the Far East. This part of our book we have called " The Apprenticeship of Toil." It discusses the *general* acquisition and application of skill which necessarily preceded attempts to harness the forces of Nature, and to develop power engineering as a specialised branch of engineering activity. It also gives particulars of some of the ingenious devices invented during the last few centuries before the Christian era—water clocks (including Plato's alarm clock), fire engines with pistons and cylinders machined in the lathe, a coin-in-the-slot machine, a torsion machine gun, a taximeter for recording distances travelled in a chariot, and so on.

The second part of our book, entitled " The Age of Power," continues the story from Græco-Roman times. Here we tell of the earliest known experiments with steam, the origins of the water-wheel and the windmill, the evolution of the steam engine, the development of the water-wheel into the water turbine, the origins and development of the internal combustion engine, the steam turbine, and the electric generator. Here also we give a general survey of modern practice, and the latest developments in the production and distribution of power.

In the third part we have discussed past and present methods of winning and treating the fuels and metals without which power plant as we know it could not exist. Naturally enough, we have given most space to the mining and treatment of coal, and the manufacture of steel—substances which in modern times have proved to be more marvellous than any dreamed of by alchemists of old. In conclusion, we turn to the World Power Conferences, and glance at some of the possibilities of future development in power engineering.

A desire to compress the whole work into small compass has necessarily reacted upon the amplitude of our survey. After some hesitation we cut down the space allocated to the development of windmills and water-wheels, as we are discussing this stage in the quest for power in greater detail elsewhere. Again, much interesting material concerning special power plant developments for transport purposes was reluctantly set aside altogether. It was best, we decided, to concentrate in the main upon developments leading up to, and closely associated with, modern central power station practice.

Every endeavour has been made to ensure accuracy of statement throughout this work. It would be too much to hope, however, that errors have been entirely avoided, and accordingly we take this opportunity of saying that all corrections will be gratefully acknowledged.

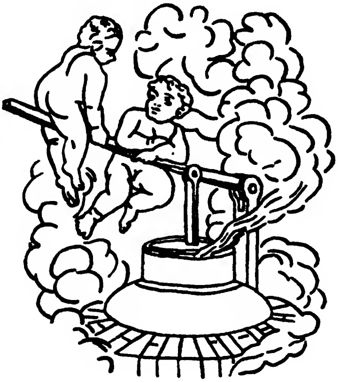
The need for some general survey such as we have attempted here will, we think, be obvious enough. We have on our shelves histories of many other kinds of human activity ; but though invaluable work is being done by the Newcomen Society, and the History of Science Society, and though there are a few histories devoted to special phases of engineering progress, no comprehensive history of engineering—no history even of power engineering—has so far as we can trace yet been written. Nor has any connected and systematic survey (not merely a condensed encyclopædia) of modern power engineering progress, displayed in its proper perspective against a historical background, and suitable for the general reader, so far been made. Yet never was there so widespread an interest taken as now in machinery and the giant forces which have been harnessed to drive it. Whichever way we turn we find a mechanical invasion of human affairs in full swing. In factories, in offices, on the farm, in the home, throughout whole continents we see power-driven machinery increase and multiply, spreading to the ends of the earth and the uttermost parts of the sea. Great power schemes are constantly being developed, power cables and their supporting towers are rapidly becoming familiar features of the countryside, while the products of power and machinery affect each one of us from the cradle to the grave. And the end is nowhere in sight. On the contrary, it is clear that such developments are even now only in their initial stages, a mere foreshadowing of what is still to come. So, gradually, first one and then another onlooker wakens to the fact that we are now faced with changes different from any we have ever known before, changes which must revolutionise the whole life of man from top to bottom. With this realisation comes a desire to know more about past and present progress in power engineering ; to arrive at some clear understanding of what it is that has made these amazing changes possible, and of how the never-ending quest for power is likely to react on human affairs in the years to come. If our book, in spite of its many imperfections, proves to be of service in this regard, we shall feel amply rewarded for the time and care expended upon it.

Our thanks are due to all those who have kindly given us the benefit of their advice and criticism at one point or another in this book. We are specially indebted to Professor John L. Myres, M.A., D.Sc., Wykeham Professor of Ancient History in the University of Oxford ; Professor William A. Bone, D.Sc., F.R.S., Professor of Fuel Technology in the Imperial College of Science ; the late Sir Charles A. Parsons, O.M., F.R.S., inventor of the steam turbine and for many years head of the great engineering firm which bears his name ; and Mr. A. H. Fitt, M.I.Mech.E., who has specialised in steam turbine design. Between them they read and criticised the bulk of the work in manuscript. We must also record our gratitude to Sir Robert A. Hadfield, D.Sc., F.R.S., who not only took a kindly interest in the progress of the book, but also supplied us with valuable information of metallurgical and historical interest. We must, however, emphasise the fact that we ourselves are entirely responsible for all statements embodied in the text.

Formal acknowledgment for the loan of blocks has been made beneath the illustrations, but in this connection we would like to record our appreciation of the assistance generously afforded by public bodies and engineering firms here and abroad ; also by Mr. W. H. Dickinson, M.I.Mech.E., Honorary Secretary of the Newcomen Society, and Mr. J. J. Conlan, Assistant Editor and Manager of *World Power*.

Among works we have found invaluable for reference are Bone's *Coal and its Scientific Uses*, Hadfield's *Metallurgy and its Influence on Modern Progress*, Hart's *Mechanical Investigations of Leonardo da Vinci*, President Hoover's translation of *De Re Metallica* by Georgius Agricola, Usher's *History of Mechanical Inventions*, and Sarton's monumental work, *Introduction to the*

History of Science. Finally, we desire to pay a tribute to the memory of two pioneers in engineering history, Robert Stuart and Thomas Ewbank. Had we not been introduced to Stuart's *Anecdotes of Steam Engines* (London, 1829) by our friend Mr. W. A. Scott, M.I.Mech.E., M.I.E.E., our interest in the history of engineering might have lain dormant for years. Ewbank's *Hydraulics and Mechanics* (New York, 1842) we "discovered" for ourselves. To the pleasure derived from reading these two works our own book *The Quest for Power* owes its existence. In it we have reproduced a few of the quaint vignettes which add to the interest of Stuart's "Anecdotes."



BOOK ONE

THE APPRENTICESHIP OF TOIL

> ". . . He can use Tools, can devise Tools : with these the granite mountain melts into light dust before him ; he kneads glowing iron as if it were soft paste ; seas are his smooth highway, winds and fire his unwearying steeds. Nowhere do you find him without Tools ; without Tools he is nothing, with Tools he is all."
>
> THOMAS CARLYLE.

CHAPTER I

MAN THE TOOL MAKER

I

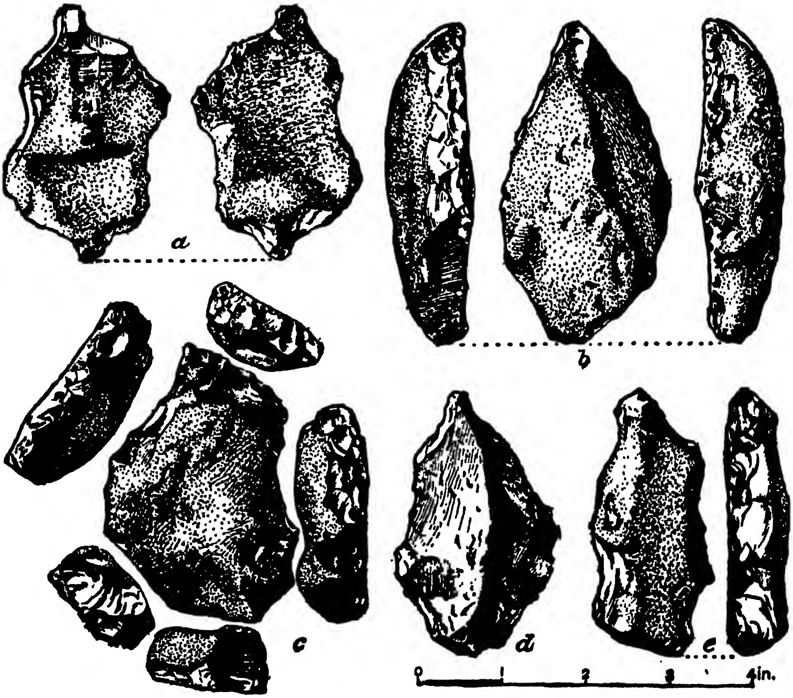
Early Extensions of Bodily Power

THE debt which modern civilisation owes to the engineer has never been sufficiently stressed. The engineer himself is seldom much in evidence. Like some unseen prompter behind the wings of a theatre, he may never take a call. The spotlight turns upon the politician, the popular novelist, the pugilist, the cinema star—all manner of entertaining people—but only on the rarest occasions does the engineer become a centre of public interest and discussion. Nevertheless, it is he who provides all the intricate and beautiful machinery which binds our civilisation together. His hand and brain are everywhere, he harnesses the forces of Nature, lights our cities, constructs our roads and railroads, girdles the seas with ships, builds airplanes to compete in speed with the wings of the wind, and—to-day with sound, to-morrow with sight—is rapidly enabling each one of us to exclaim with John Wesley : " The World is my parish."

Of all his contributions to social evolution none is of such supreme importance as control over the forces of Nature. This control now plays so vital a part in human affairs that we are apt to take it for granted, like the water we drink or the air we breathe. So it is that the apprenticeship of laborious toil, to which the whole human race was subjected through countless centuries, tends to fade from the memory of civilised man.

Yet until control of power has been traced back, step by step, to its first-beginnings in the remote recesses of the past, its true significance can never be adequately grasped. Only in the light of history is it possible to see the engineer-made world of to-day in its true perspective. We propose, therefore, before discussing the truly marvellous advances made in power engineering in recent years, to tell the story of man's quest for power from prehistoric times to the present day.

It will be manifest that there could be no *conscious* quest in the earlier stages of human development. But from the first we find evidence, in the form of flint tools, of man's endeavours to extend and amplify his own bodily power. This was the beginning of an education which was some day to enable him to harness external power. In this first book we shall consider some of the ways in which the knowledge and skill so acquired were increased and applied to the requirements of mankind through five or six hundred thousand years.



(*Courtesy of the British Museum.*)

Eoliths, the earliest known type of tool.

No doubt man was already endeavouring to add to the effectiveness of hand and arm whilst still in the sub-human stage of evolution. We know, indeed, that even a chimpanzee can crack nuts with a stone, and has been observed to make intelligent use of sticks to move objects which would otherwise have been too heavy for him. So also with the other anthropoid apes. " I have myself," says Darwin, " seen a young orang put a stick into a crevice, slip his hand to the other end, and use it in the proper manner as a lever." [1] But despite these and similar instances which might be quoted, there is no record of any mammal other than man that can fabricate implements, none that can shape tools to meet special needs. In this regard at least there is an unbridged gap, a link that is still missing between man and his fellow creatures.[2] That there may have existed at some time past several distinct species of human beings now extinct is a matter we need not stress here. It suffices for our present purpose to know that all human beings of whom we find any trace were tool-makers, and in this respect different from every other living creature. No matter what his stage of development, man so far as our knowledge goes has always possessed the instinct and capacity destined to make him in the end a creative craftsman, a mechanic, and an engineer. Even the earliest specimens of artificially shaped tools indicate an order of intelligence beyond that of any known ape or monkey. An intelligent ape might possibly note that one stone when struck against another sometimes breaks in pieces. But no ape has been known to deduce, from his experience of the sharp edges thus provided, that scrapers and cutting tools might be artificially made at will. It required the superior brain and upright posture of man to make effective use of the possibilities thus presented to his attention ; though it may be that centuries passed during which the art of tool-making was learned and lost and learned again before it became a commonplace of daily routine.

Here, then, in this first section we gain a glimpse of our early progenitor, able to use sticks as levers, no doubt also equipped with clubs and staves of wood, and knowing how to make simple tools of flint. It is probably not too much to assume that he was also acquainted with some of the possibilities of the inclined plane, more particularly as exemplified in the wedge. With the passing of time he would gradually acquire greater manual skill ; learning, through direct perception of substance and form, long before he began to reason about the " how " and " why " of what he was doing. So knowledge would come to stay, the priceless heritage of the race ; enabling man to apply his bodily power to greater advantage, to modify his environment, and so take a hand in moulding his destiny.

---

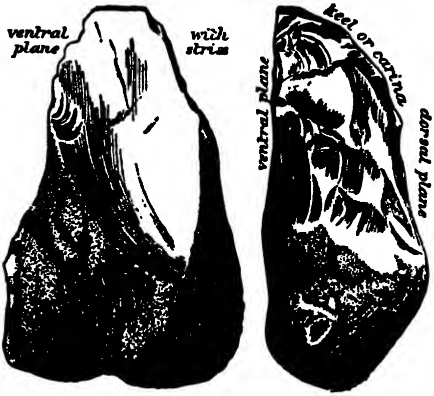
[1] *The Descent of Man*, p. 124.

[2] The orang at the Zoo which escaped temporarily a few years ago constructed a file of twisted wire and cut through a cage-bar with it.—J. L. M.

2

How the First Tools were Made

The earliest implements bearing evidence of having been shaped by the hand of man are of a very elementary nature. They are found in large quantities in various parts of the world, though naturally enough the most interesting " finds " up to the present have been made in Europe. England in particular has provided a remarkable number of valuable specimens, many



(Courtesy of the British Museum.)

Rostro-carinate flint. One-third full size.

of which have been discovered in East Anglia. They consist, for the most part, of pieces of flint roughly flaked along one or more edges. Some have been chipped, so that one end resembles the beak of a bird, or the keel of a boat reversed. To this they owe the name " rostro-carinate " which has been given to them. Crude as they are, they indicate intelligence and skill in the making. As century followed century this intelligence and skill increased, and was applied to the manufacture of tools involving more careful and elaborate workmanship.

It is interesting to note in this connection that man was particularly well equipped, not only for handling whatever attracted his attention, but also for seeing clearly the objects handled. We must picture the not-quite-human ancestors of early man as being forest-hunting, tree-climbing creatures, with fore-limbs highly developed for prehensile purposes. But early man himself, having in general abandoned the arboreal way of life, was able to acquire a keener, more delicate, touch than either the apes which still habitually used their fore-limbs for climbing, or the beasts which ran about on all fours. With this readiness of hand went exceptional accuracy of sight. For, alone among mammals, man and the apes have on their retinas an area of exact vision. This area, very sensitive to light, and known as the yellow spot or *macula lutea*, is of the highest importance in estimating shape and judging distance. It enabled man to observe, to discriminate, to hold, to strike, to throw, with greater assurance. So hand and eye worked together with a developing brain.[1]

---

[1] In the primitive vertebrate behaviour is dominated by the sense of smell, a sense which is of little value as a means of apprehending spatial relations. A necessary preliminary to the emergence of man as a tool-making, tool-using animal was the substitution by his sub-human progenitors of sight for smell as the controlling factor in behaviour. With this came the ability to make swift, controlled, conjugate movements of the eyes, including the act of convergence, which resulted in overlapping of the visual fields and the development of stereoscopic vision. This led to an appreciation of form, solidity, relationship, and a power to discriminate between substance and shadow, light and shade, previously unknown. Finally: " The development of *maculæ luteæ* made possible the fuller appreciation of the details, the texture, and the colour of objects seen, and in association with the increased precision of muscular control enabled the eyes to follow the outlines of objects and appreciate better their exact size, shape, and position in space. But this completer vision of objects in the outside world stimulated a curiosity to examine and handle them, and so led to still further

And to this co-ordination of hand and eye man's upright posture contributed to a degree that can hardly be overstressed. His hands were thereby freed, once and for all, to respond to the varying dictates of his will, or to the promptings of curiosity, cupidity, or fear. He was able to express himself creatively ; to give external embodiment, on no matter how restricted a scale, to thoughts and preferences that filtered through his mind. With this would go the body balance, the firmness of "stance," so essential when making and using tools. And other things being equal, those best equipped for self-defence and for obtaining food in the ways we have indicated would be most fitted to survive. There would thus be a constant tendency for the race to advance in mental alertness and manual dexterity.

It is difficult for the modern engineer, accustomed as he is to an almost inexhaustible wealth of devices for holding, manipulating and shaping materials, to realise the degree of skill necessary to chip nodules of flint to a required shape, with nothing but one hand for a vice and a stone held in the other hand for a hammer. Mr. J. Reid Moir has shown, by experiments in chipping and shaping flint, that a definite procedure is necessary to produce tools similar to those made by early man.[1] First it is necessary to break off a portion of the flint nodule to provide a flat surface, or "striking platform" as it is called, on which blows can be struck with precision for removing flakes. A striking platform is considered by experts to be one of the fundamental necessities of flint implement making. A series of blows delivered round the edge of this platform will result in portions of the flint falling away in the manner necessary to obtain the sharp edges desired. But the finer flaking at the cutting or scraping edges of later or more skilfully worked specimens appears to have been produced by pressure. Implements which it is believed were made specially for this purpose have been found in Suffolk and elsewhere.

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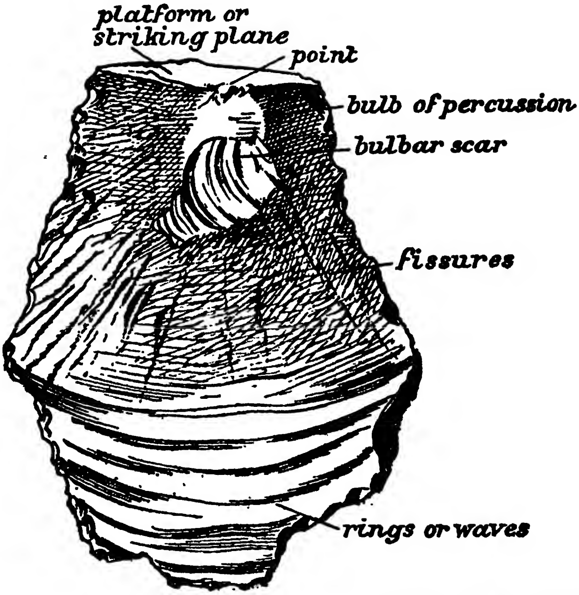
cultivation of skill in movement and an enhancement of tactile discrimination."—Elliot Smith, *The Evolution of Man*, p. 153.

[1] J. Reid Moir, *Pre-Palæolithic Man.*

It is possible that at first flints already possessing flat surfaces were selected ; and later, with increasing manipulative skill, it may have been found possible to obtain the flat surface itself by flaking. But in general there is good evidence that the initial step was to secure, in one way or another, a suitable striking platform as indicated by Mr. Moir. Anyone who cares to experiment for himself will speedily realise the great difficulty in detaching flakes from a rounded flint surface by striking it with another piece of flint or stone. The force of any blow applied obliquely is deflected. If we consider components of such a force, tangential and normal to the surface respectively, we see that much of the striker's effort is wasted, to an extent depending on the obliquity of the blows delivered.



(Courtesy of the British Museum.)

Diagram of flint fracture, showing striking platform.

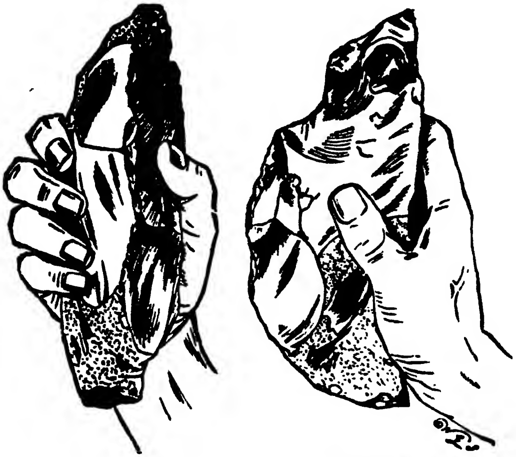
Flint is a variety of silica found in the form of nodules in the upper chalk beds and in similar limestone deposits. Its origin has not been satisfactorily explained. To early man it no doubt seemed as important as steel seems to us to-day. Some of his raw material he obtained from gravel deposits consisting of flint and other stones washed down by the action of water. But already at this early period man appears to have begun his career as a miner. Near Brandon, in Suffolk, and in other places, hundreds of circular depressions have been discovered, which can only be accounted for by assuming that they mark the sites of prehistoric shafts sunk to the level of the better quality seams of flint ; horizontal galleries having then been driven from the shafts into the seams. Deer antlers, which were evidently used as picks, with the chalk still adhering to them, have been found at these sites. Specimens are to be seen in the British Museum.

Acquisition of Skill and the Discovery of Fire

The natural conditions surrounding primitive man were such as to foster every latent tendency to become increasingly alert and skilful. Western Europe was the haunt of the mammoth, the rhinoceros, the hippopotamus, the sabre-toothed tiger, and other creatures equally inimical. It can hardly be doubted that besides weapons of flint (and sometimes of quartzite where flint was not available) man even then, as already suggested, had staves and clubs of wood which he used as weapons of self-defence, or as levers and other implements shaped and adapted to extend the possibilities of his own bodily frame and muscular power. Armed with these he would be able to defend himself against attack, and sometimes even take the offensive against animals far better equipped by Nature than himself.

Later he had to contend with another enemy, the first Glacial Age, which menaced him but failed to overwhelm him altogether. From then on, save for continued evidence afforded by his flint tools and weapons, we learn little of his adventures through a vast space of time, until he appears again with larger and better shaped tools at his command.

These tools, using the word to include weapons, are called "Chellean," from having been found in the early days of archæological research at Chelles in France. Many of these are almond-shaped, pointed at one end and rounded at the other. This form was obtained by flaking on *both faces.* The degree of skill required in their manufacture, having regard to the meagre facilities available, will be apparent to anyone who attempts to copy them. A specialised, and perhaps later type of Chellean tool, known as the "Acheulean," shows greater care and more diversity of shape. In some cases it may have been fitted to a handle and used as an axe. Hammer and anvil stones have also been found, scrapers, flints apparently used for planing, and knives. The latter are nearly always of a delicate workmanship. Man at this time lived by hunting and fishing and was familiar with fire.



(*Courtesy of the British Museum.*)

Stone Age chopping tool. Quarter full size.

Man was familiar with fire ! Charred wood and bones in the deposits of Acheulean times (possibly as much as 200,000 years ago or more, but less according to some authorities) are our evidence.[1] When the first man to discover the secret of making fire saw flames and smoke gathering under his hands we do not know. It was one of the most epoch-making events in the whole history of mankind.

---

[1] Osborn, *Men of the Old Stone Age.*

No doubt fire had long been familiar as a wonder and a menace before it was made at will. It may first have been secured from some burning forest, or a tree struck by lightning, and preserved. The chance ignition of tinder by sparks from two flints struck together, or more probably flint and iron pyrites, may have brought an answering flash of intelligence in the mind of some man who saw it.[1] Later would come the production of fire by means of the simple fire drill with a spindle twirled between the hands, and the fire plough consisting of a stick held at an angle and rubbed vigorously in a grooved piece of wood. Later still man would devise the improved fire-drill in which the spindle is rotated by a piece of cord or a bow. But, however produced, it provided man with warmth and light, a new defence against attack by wild beasts, and a means of cooking his food. With it he has since been able to modify materials, extract and mould metals, and utilise the latent energy of coal and oil. With the discovery of how to make and control fire a whole new world of possibilities was indicated for man as an engineer, though hundreds of thousands of years were still to pass before he showed the remotest apprehension of this fact. Meanwhile, the cooking of food led to a reduction in the muscles used for masticating, and so facilitated the frontal activity of his brain.

European man at this time was still liable to attack by the mammoth, the elephant, the woolly rhinoceros, the cave-lion and other animals with which he must have been in constant conflict. And now his climate was steadily changing once more. Yet another—the third—Glacial Age took the world in its grip, until the north of Europe and most of what are now the British Isles (then probably joined to the mainland) were frozen over. Ocean levels were altered by a vast formation of ice, and with them the contours of continents and islands.

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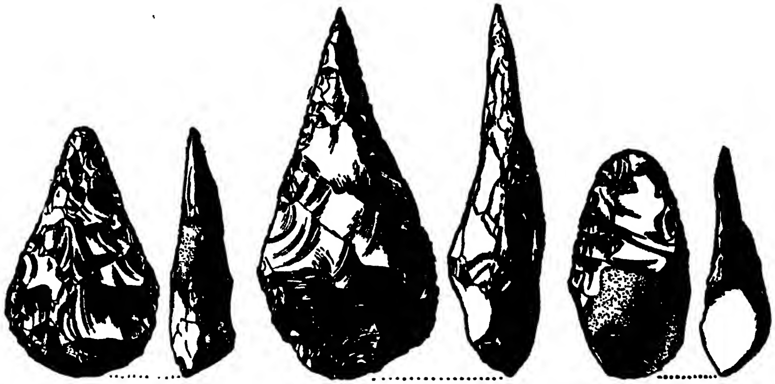
[1] It is interesting to note that Lucretius suggests lightning, and also the heat engendered by the friction of tree branches rubbing together when swayed in the wind.—*De Rerum Natura,* V, 1090–1100.

Even beyond the fringes of the ice cap the temperature must have been considerably lowered. Life was becoming harder. The elements must have appeared to be conspiring with the beasts to overthrow the maker of tools and fire.

But still he survived, and we find a descendant, Neanderthal man, in what is known as the Fourth Glacial Age—say 30,000 to 50,000 years ago. In spite of this prodigious lapse of time, he is still only working in flint and wood, with occasional use of other kinds of stone. Mental development is cumulative; the more man develops the more he reacts on his environment, and the greater the possibility of his further development.



(*Courtesy of the British Museum.*)

Front and side views of flint implements from Suffolk. Quarter full size.

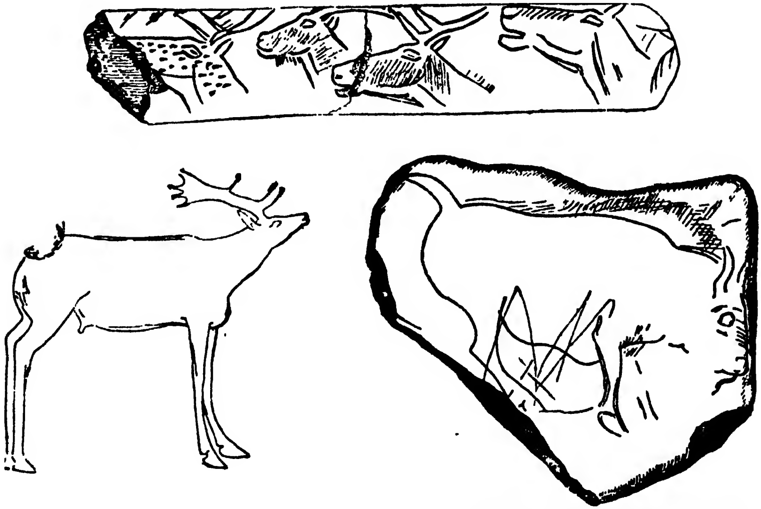
But at that time his environment called for little more than alertness in sight and movement and touch. He was still only a savage with a few special aptitudes. The increasing cold had driven him into caves, from which he probably had first to drive out the beasts already inhabitating them. In one cave which he inhabited at Echnoz-la-Moline, as many as 800 skeletons of bears have been found.

Flint tools had by then become smaller, but on the whole indicated further advances in skill and variety. Scrapers, and notched blades suitable for hafting, have been found belonging to this (the "Mousterian") era. Also almond-shaped points and flints shaped for piercing. Many of these are worked on one side only, and more carefully pointed than the products of earlier times. It has been suggested that the race of beings who made them eventually died out, but the evidence is not conclusive.

4

Primitive Art in Relation to Engineering Progress

At last, however, it may be about 20,000 years ago, some newcomers appeared in Europe who were far above the Neanderthal level of intelligence and achievement. Collectively these are known as "Reindeer man" because of the many drawings of reindeer which they made.



(Courtesy of the British Museum.)

Examples of prehistoric draughtsmanship.

Climatic conditions were at the time of their first appearance becoming more favourable, though still cold and showing considerable diversity in the various parts of Europe. The glaciers receded, and great areas became covered with grass. Behind the grass came forests. Animals characteristic of these types of vegetation followed. Whatever at this time was stimulating man to higher cultural levels, the reactions on his craftsmanship are very apparent. His tools are finer and more elaborate, and he shows not only considerable development of inventive faculties but—a new thing in history—artistic gifts as well. Reindeer man at the height of his development became an artist of surprisingly realistic powers. With the products of this artistic impulse we are not particularly concerned here. What does interest us is the mental development underlying that impulse. The relationship of the artistic sense to man's constructive ability is a matter which merits more consideration than it commonly receives at the present time. We cannot pause to discuss this matter in any detail ; but the suggestions are made in passing that not only is engineering an art as well as a science, but that the engineer at his best may be a creative artist whose work is just as beautiful as that of any painter or sculptor ; and that upon the development of man's artistic sensibilities in the past the quality of his engineering work now and in the future in no small degree depends.

Certainly the faculty in Reindeer man of intensive concentration, his manifest powers of careful observation, his sense of proportion, deftness of touch, ability to make tools specially designed and wrought for fine draughtsmanship, were matters of the greatest moment in the evolution of a mentality which was destined at last to achieve control over the forces of Nature. Man at this time must clearly have been capable, with suitable stimulus, of reaching out to far greater diversity of constructive achievement than is indicated by his dexterity in shaping flint. Moreover, it may be noted that some of his drawings are coloured ; and in these initial experiments with pigments, involving an empirical mixing of powders and liquids, it may not be altogether fanciful to see the first dim beginnings of what was some day to lead—through magic rites and alchemy—to the modern science of chemistry.

In the making and use of tools Reindeer man was, within his limitations, nearer to the skilled mechanic of to-day than to his predecessor Neanderthal man. He knew not only how to shape flint into forms and having a finish hitherto unknown, but also to work in bone and horn and ivory. Some of his flints are provided with a tang for hafting, some have serrated edges for sawing, others form razor-like blades as thin and almost as sharp as steel. Yet others have been made—and quite beautifully made—into awls, drills and graving tools. The drills are believed to have been used for piercing or drilling the eyes of needles. The needles themselves were made of bone and are examples of very fine workmanship indeed. Specimens have been found in France together with tools and material used in their manufacture. The method commonly adopted appears to have been to take a splinter from a bone by means of a suitable tool, the splinter being rounded by using a serrated flint which was in effect a file. Then the surface was burnished and the needle pointed by rubbing on a sandstone burnisher, the eye being drilled with a pointed flint. In addition there are bone pins, spatulas, harpoons, spearheads, throwing sticks, and other implements. The throwing sticks are of interest as illustrating a method of increasing the propelling power of the human arm. None of the flint tools are polished, although great ability and precision is shown in finishing and polishing tools and implements of bone.

No doubt concurrently with all this man was developing his wooden tools and instruments, though there is no reason to suppose that he had as yet attempted to build elaborate structures of wood. Agriculture had not yet begun, nor was there any domestication of animals ; but there would be rough shelters of branches and skins or rushes to build, and much constructive skill would be devoted to the making of traps, fishing accessories, spear handles, arrows and many other items in the equipment of a life which still centred about hunting. No doubt also skins were being dressed and stitched together into roughly made garments.

And now towards the end of this period the climate became damp and warm, the reindeer went north, the mammoth, aurochs and other large mammals disappeared. With them Reindeer man as a distinctive type practically disappeared too and we see no more of his remarkable artistic efforts.

In the final stages of the Reindeer Age, or shortly after, a people now known as Azilians left traces of their wanderings in south-west Europe. This was probably between 10,000 and 15,000 years ago. The world was beginning to assume climatic conditions and land contours such as we are familiar with now. The most interesting thing we know of this people is that they left behind a great number of pebbles painted with peroxide of iron. There are designs which consist of one, two, three or more dots, in some cases stripes, crosses, circles, and sometimes combinations of form resembling certain characters in the oldest-known Mediterranean alphabets. It has been suggested that the dotted and striped pebbles were used for counting, and that the mental activities thus indicated bear much the same relationship to the intricate calculations of the modern engineer that flint tools bear to the complex machine tools of the present day.

We have now followed man in his laboriously slow yet unmistakable acquisition of skill through some hundreds of thousands of years. Towards the end of this period he had also become a worker in horn and ivory and bone. And, as we have noted, he had given proof of being a keen observer and an admirable artist when his interest was aroused. Of the Reindeer peoples the best developed was that which is known as the Cro-Magnon race. Unusually tall and well built—one skeleton measures 6 feet 4½ inches, while others are well over 6 feet—and equipped with a cranial capacity indicating a people " capable of ideas, of reasoning, of imagination," this race is considered by Sir Arthur Keith to have been one of the finest the world has ever seen. Nevertheless, it appears to have been physically and mentally susceptible to changes of climate. Later specimens attest to loss of stature ; and there are indications that during a temporary return of glacial conditions their abilities waned. Then after a relatively brief revival the distinctive culture of this people left no further traces. The stage thereafter is occupied by Neolithic man, who brought with him to Europe an altogether higher level of culture. In our next chapter we shall discuss this culture and the evidence of engineering progress which from our point of view was its most significant feature.

CHAPTER II

THE DEVELOPMENT OF CRAFTSMANSHIP

I

Beginnings of Culture and Specialisation

The new phase of human existence known as the Neolithic age began in western Europe perhaps between 8000 and 2000 B.C. Neolithic man appears to have come to Europe rom the East, bringing with him more diversified ways of ving and evidence of greater control over his environment. The design of some of his flaked implements was introduced rom the East; and, of his earlier domesticated animals, sheep were certainly not European, while the nearest living relatives o his goats are found in Asia. There is evidence that domestiation of the horse also came from the East; the Kassite peoples probably having introduced the horse into Mesopotamia from he Persian plateau.[1] Again, he cultivated wheat. Now this cereal, previously unknown to Europe, grows wild in Syria; which also points to an Eastern origin for these newcomers who brought with them such novel ways of living.

It will be seen that so far as Europe is concerned, man at this time made an extraordinary stride forward. Hitherto he had subsisted on the natural food supply of the country in which he lived. He had been a wanderer, following the herds from which he obtained meat and skins, and no doubt learning to distinguish edible plants and berries when not too preoccupied with his hunting expeditions. Now, after a relatively short lapse of time, we find him tilling the soil and growing crops, storing food, taming animals, keeping them as a source of supply and probably using them to augment his bodily powers for ploughing and transport. And now he began to show an inclination to settle down, to remain in close proximity to his crops and the accumulating gear which became more and more necessary for his new way of life. His conception of property must have been greatly strengthened, involving increased watchfulness and a permanent dwelling-place where at need he could conceal the more valuable of his implements and other possessions. And so as time passed by he settled down to the round of ploughing, sowing, weeding, harrowing, and reaping which we now regard as the normal social life of agricultural communities.

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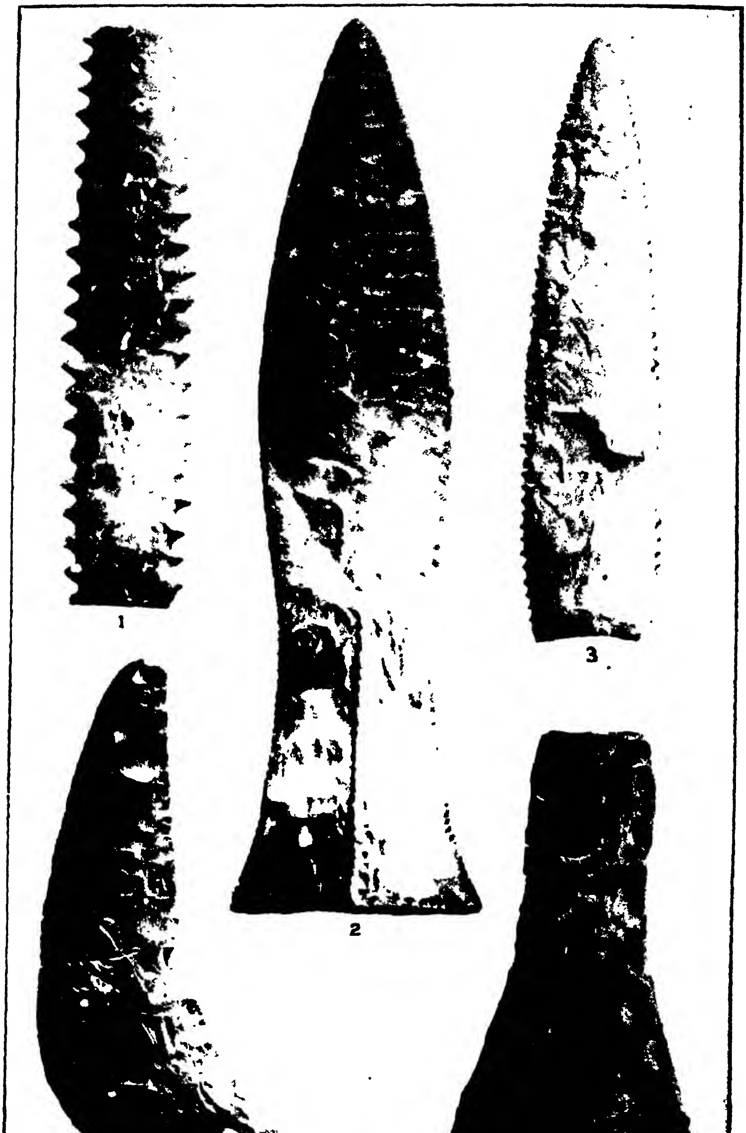
[1] It is perhaps significant that the Babylonians called the horse "the ass from the mountains," and that round about 2000 B.C. a people dwelling in the neighbourhood of Lake Van excelled in horse-mastership and possessed a treatise on the training of horses.—Sidney Smith, *Early History of Assyria*, p. 214.

We have referred to the " Neolithic " Age in accordance with custom, but the term is not very satisfactory. It is true that novel methods of shaping stone were introduced, such as grinding and polishing, but this is only one of many features by which the new culture is identified. Among others of the highest importance may be mentioned plaiting, weaving, and pottery making. Moreover, flint flaking still persisted side by side with the art of polishing stone ; and manufacture of both types overlapped with periods in which copper, bronze, and finally iron, were used. Thus, while stone tools still prevailed in western Europe, a Copper Age had already dawned elsewhere ; so that, although for convenience we may continue to refer to the Neolithic Age, it is very desirable to bear these qualifications in mind.

The many new developments which made their appearance in Europe with Neolithic man must have been based on centuries of experiment and experience elsewhere. We have given reasons for concluding that he came with the fruits of this experience from the East. It is probable that he found conditions much harder in the region to which he migrated. But by means of his numerous inventions and discoveries and his increasing knowledge he was able to form a buffer between himself and the severer stresses of life. He accumulated wealth in the form of food, flocks, herds, skins, and tools, and began to multiply in numbers beyond all precedent. And now specialisation of skill also became possible. By turning the



(Courtesy of the British Museum.)

Neolithic flint implements.

dexterity of each individual into a particular channel the race as a whole increased its possibilities of material advancement. For when each individual in a group concentrates for the most part on some one particular kind of employment, then, other things being equal, the productive powers of the group must be considerably augmented. Not only does each worker acquire greater dexterity, but there is also a marked saving in time through no longer having to turn constantly from one kind of work to another. Moreover, as Adam Smith remarks: " Men are much more likely to discover easier and readier methods of attaining any object, when the whole attention of their minds is directed towards that single object, than when it is dissipated among a great variety of things." This remark, applied by Adam Smith to the division of labour, applies also to that concentration on a particular group of activities which we call specialisation. Whether or not it is altogether desirable that any human being should spend his life directing the whole attention of his mind towards a single object is a matter we cannot discuss here. It will suffice for our present purpose to suggest that man had begun to specialise as far back as the Neolithic Age, and that this development was accompanied by a degree of material advancement such as he had never known before.

Man increases his Range of Skill

There is yet another aspect of man's progress at this time which it is very important to note. He had begun to look ahead and to make provision for the future.

Hitherto he had lived very much from day to day. Once the skill necessary for satisfactory flint flaking had been acquired, the labour involved in maintaining the requisite supplies would not be great. But grinding and polishing, though perhaps requiring less dexterity, necessitated greater patience. A well-ground and perforated axe-head might take weeks and even months to make. It would no doubt be brought out at intervals and put away again for finishing at the maker's convenience. This implies foresight and restraint, the giving up of present advantage to meet future needs. Particularly does this apply to the perforation of axe-heads and hammer-stones, if, as seems probable, this work was accomplished by means of sand and a blunt stick. Even though at a later date he may have invented a tubular drill of reed, still the process must have required patience and perseverance—qualities very essential to engineering progress.

All things considered, man would appear to have reached a highly important turning point in his apprenticeship of toil. He had long been skilled within sharply defined limits. But beyond this his progress for many centuries had been remarkably slow. Indeed, without some new stimulus to urge him on to a greater amplitude of constructive effort, he might very conceivably have remained a flint-chipping savage for all time. But now, having begun to accumulate property, to specialise, to take thought for the morrow, and to learn self-discipline, he soon found hitherto undreamed-of outlets for his latent constructive powers.

In consequence we find Neolithic man speedily acquiring a much greater *range* of skill, making experiments, testing materials, becoming more methodical, seeking new ways of satisfying his more diversified needs, showing an appreciation of form, and feeling his way to control over the forces of Nature. In short, he was becoming more of an engineer. His use of the bow, and of long wooden handles for axes, indicates practical acquaintance with elasticity and some of its applications. With well-made axe and adze and hammer-stone he was able to hew his way to mastery over the forest. And with saw and chisel and planing tool, even though only of stone, he could shape timber to his requirements. Home-building with wood framework and roof thatching followed. The remains of his lake dwellings, the careful fitting involved in attaching his hammers and axes to their helves, the split and ground pebble type of implement which with careful usage maintained its own edge, all show constructive skill. The fact is that Neolithic man, from an engineering point of view, was far more than a tool-maker. He was also a fitter, an assembler of parts, and an erector of structures. He erected structures to live in, and in many places devoted much time and labour to the erection of great stone chambers in which to bury his dead. He also quarried, transported and erected vast pieces of stone, which apparently bore some relation to his religious rites, as in the well-known instance of Stonehenge.

Stonehenge

Stonehenge affords a notable example of the way in which man now reached out to new possibilities of constructive achievement. Looking at these huge slabs of stone one feels that the experience gained in quarrying, in heavy transport, in erection, and in organisation, by those responsible for planning and supervising this remarkable work could never be altogether lost again. It is clear that the work of large gangs of labourers must have been carefully organised and directed over a long period of time. The engineers in charge must have had both imagination and ability to an unusual degree. This may very well have been developed by experience gained in connection with similar work on a smaller scale. The small stones forming the inner ring and those in the oval or horseshoe about the altar are believed to have come from the Prescelly Mountain in North Pembrokeshire. It may be that they had previously formed in that locality a smaller "Stonehenge," as the remains of several stone circles can still be seen there. The altar stone also may have come from that region, as it is of similar composition to the old red sandstone which is to be seen on the north shores of Milford Haven. The inner circle and horseshoe stones are certainly not of local origin, and, as they have characteristics not found elsewhere than in Pembrokeshire, the belief that they came from that county appears to be well founded. The great outer stones, on the contrary, were almost certainly obtained from near at hand.

How the inner stones were transported across the intervening distance of some 180 miles is entirely matter for conjecture. Geoffrey of Monmouth, writing in A.D. 1130, says that the Devil brought them from Ireland in one night. This one would imagine would be a tough job, and apparently the Devil found it so, as he is alleged to have dropped several stones on the way. It is more consonant with modern ideas to assume that the work was carried out by ordinary human engineers. That it was completed before the Age of Bronze had dawned in Britain is indicated by the fact that, although much of the earth about the stones has been put through sieves of one-eighth inch mesh, no weapon, tool, implement, or ornament of bronze has been found, though stone and horn tools have been discovered, such as flint axes, mauls, hammer-stones and reindeer-horn picks.[1]

The simplest way to bring the stones from Wales would have been to float them on rafts up the Bristol Channel, up the Bristol Avon, and so to the point where Bradford-on-Avon now stands. They may even have been floated as far as Melksham, which is about eighteen miles from Stonehenge. How, if this method were adopted, the rafts were propelled against the stream it is, of course, impossible to say. Legend has it that a great boulder, which can be seen in the depths of the Avon near Bulford, is one of the stones which the Devil dropped on his way through the air. It may very well be that a raft capsized at this point, as it is unlikely that engineering work on so large a scale was carried out without mishaps of one sort or another.

Many theories have been propounded in connection with the erection of the stones. The easiest method would probably have been to haul them up a ramp on to mounds of earth specially prepared, and then tip them over into holes provided for their reception. We shall consider this process in more detail later, when referring to the erection of the great Egyptian obelisks. Whatever the method, it must have been an exceedingly difficult task. The uprights of the outer circle are estimated to weigh from 20 to 40 tons each, and the cross pieces 6 to 8 tons. The latter also could have been placed in position by piling temporary mounds about the uprights.

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[1] A *stain* of copper is said to have been observed on one of the stones exposed during excavation.—J. L. M.

The difficulty involved in manhandling without lifting tackle may perhaps be indicated by the fact that when, in A.D. 1919, some of the stones which were leaning over were restored to an upright position, many months were required for this task, even with the use of cranes and other resources of modern engineering.

Ability to organise large bodies of men working together for a common end must have been developing for a very long time before work on the scale of Stonehenge was undertaken. There is reason to suppose that as far back as the time of the Cro-Magnons some sort of team work had already begun. Certain curiously carved and shaped pieces of reindeer horn have been found in the caves which Cro-Magnon man occupied. It has been suggested that these were symbols of leadership. Hence the name " bâtons de commandment " which has been given to them. Bone whistles of the same period have been found. It is possible that in chasing large game some method of organising group attacks was devised. The leader carrying his bâton would wave it and blow a whistle, directing his men here and there as occasion required. It is certainly necessary to assume some such remote beginnings to explain the large-scale organising ability displayed during the Neolithic Age.

So we see man in " Neolithic " western Europe carrying out great constructive enterprises, building homes, flaking flint, making improved tools of stone by grinding and polishing, making pottery, attending to his domesticated animals, maybe with a dog or two at his heels ; and, in rare moments of leisure, looking at the sky with the light of speculation in his eyes.

Sometimes that speculation would be about far-off things, sometimes turned inward to himself. For on his pottery we find new patternings quite different from the naturalistic art of the Reindeer period. We see circles, crescents, chevrons, rectangles and other conventional figures. If living forms are reproduced, then a preference is shown for human outlines. All this indicates an abstract conception of shape and a self-regarding quality in the potter's mind which was lacking in that of his hunting, animal-sketching predecessors. And it is even possible to deduce from the circles and crescents that man had now begun not only to notice the sun and moon, but to think about them ; to wonder what they were, where they came from and what relation they bore to his daily life. In all this he would find unlimited scope for his imagination, preparing the way for that astrological lore which thousands of years later developed into the science of astronomy.

So his life went on. Here was his dwelling-place, and there was a clearing he had made in which to sow his grain. But his agriculture was still very primitive. Early Neolithic man in Europe scratched the ground with a stone hoe, and contented himself with snatch crops. Meanwhile, certain relations of his in other parts of the world were already climbing to still higher cultural levels and reaching out to unprecedented possibilities of engineering achievement.

4

The First Towns

When man began to settle down he would naturally choose sites having special advantages from a home-making point of view. In Switzerland and elsewhere he constructed his homes on platforms built out over the waters of lakes and streams. His refuse he threw into the water, and in time many of his valuables went the same way. Sinking to the bottom they were preserved in the mud, from which numerous specimens have been recovered in recent years. Further east he was building houses of reed-matting plastered with mud. These he built in groups on the ground which formed the first towns. East and west, he made his vessels of clay ; broke them, threw them away, made new ones, designed fresh shapes, and so continued from age to age. Always from the first he appears to have used the surfaces of his pottery for the expression of his artistic impulses. In the towns broken pottery accumulated together with other refuse. Sometimes unbroken specimens would find their way to the rubbish dumps. When the towns were built in places having a definite economic or military value they were occupied by one generation after another through the centuries. Occasionally one race replaced another. In either case new ideas and customs would centre about the old sites, and still pottery would continue to be made and cast aside. Thus one layer of refuse was added to another, and as time passed new buildings were erected at a higher level than the old. In the Hissarlik mound in Asia Minor the remains of no less than nine cities have been found superimposed in this manner. The sixth of these seems to be all that is left of the Troy of the Trojan War and the Iliad. So records were all unconsciously left behind which are of incalculable value to the archæologist. The cultural advance or decline of a people, their engineering and artistic abilities, intercourse and exchange of ideas between one community and another, maybe the wiping out of a whole town and its inhabitants by an alien people—all are matters which have left legible traces behind for modern excavators to decipher and piece together into a coherent story.

In recent decades our knowledge of man's advancement during the last 5,000 years or so before the Christian era has been enormously extended by the work of archæologists. In Egypt and Mesopotamia, in Crete, Asia Minor, Syria, Persia, Baluchistan, and now in many other parts of the world men are excavating and patiently adding to our knowledge of pre-history. In Mesopotamia in particular much light has been thrown on the hitherto obscure beginnings of what were probably among the earliest towns and cities in the world. It now seems highly probable that Eridu—earliest of all cities according to ancient legend—Ur, Erech, Nippur and other ancient centres of human activity in Mesopotamia were all founded in what is called the Neolithic Age. So probably were Susa, in Persia, and Anau, to the south-east of the Caspian Sea. Concerning the earliest known dwellers at Ur, Mr. C. J. Gadd, in his *History and Monuments of Ur*, remarks that, though their houses were humble structures of reeds, posts, and mud walling, they were not mere temporary dwellings, for stones were used as pivots for the doorposts to turn upon ; a method of construction which has always been characteristic of the land and may be commonly found there at the present day. This people fabricated tools of chipped flint, manufactured weapons of copper, made pottery and painted it with decorative designs. Their sickles were of baked clay set with flints, hoe-blades were of flint, knives of obsidian flakes, while for ploughshares it is probable that they used tree branches. They had developed an archaic writing. It is, of course, impossible to date them with any degree of accuracy. All that can be said is that they lived a long time before the First Dynasty of Ur, which began, according to the latest reckoning, about 3000 B.C.[1]

Looking further afield, it is reasonable to assume that by 4000 B.C. a great prehistoric civilisation, in which town life had already reached a relatively advanced stage, extended in local pools of culture from India to all the countries and islands at the eastern end of the Mediterranean Sea. As this civilisation developed, and the towns increased in size and number, man extended his acquaintance with copper and bronze, and discovered new possibilities of utilising the principle of rotary motion. From the drill for stone work, the fire drill, the spindle and whorl for spinning, and the potter's wheel, he passed on to the rotary seal, and—as we shall see later—to sledge rollers and the wheel and axle for land transport.

The Discovery of Metals

The potter's wheel had already come into use when Susa was first founded, and in the lowest deposits at Anau the presence of spindle-whorls indicates knowledge of the arts of spinning and weaving. Moreover, in the earliest stages at Anau, the conventional designs on pottery reveal to the expert that the industry was even then approaching the end of its artistic evolution, rather than only just beginning. At Susa the earliest specimens of pottery are "finely kneaded, and turned with a marvellously delicate skill." [2]

But even more interesting to the engineer is the fact that mingled with flint knives, scrapers, saws, and arrowheads in the excavations here and at Ur, Nippur, Eridu and Lagash, rude copper implements are found. Here we have what is possibly the earliest known evidence of man's acquaintance with metal, and there is reason to believe that it was from somewhere in this part of the world that knowledge of its use ultimately spread to all civilised peoples. It should be noted, however, that copper was also known in small amounts from the dawn of prehistoric civilisation in Egypt.

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[1] See also H. J. E. Peake, *The Flood*, for these early settlements at Ur and Kish.

[2] *Cambridge Ancient History*, Vol. I, pp. 361, 362.

Copper was in general use in Cyprus by about 3000 B.C. This island was famous from very early times for its copper mines, and at a later date gave its name to the metal. And while copper made its way further and further west, a new discovery, that admixture with tin in suitable proportions resulted in a superior material for making tools and weapons, had been made in the East. By 3000 B.C. or not long after, bronze was known in Sumeria, in Crete, and probably in Asia Minor. Knowledge of this alloy appears to have reached Italy and Spain about 2500 B.C. and northern Europe not later than 1900 B.C.[1] Crete seems to have passed directly from the Neolithic stage to the use of bronze. The early civilisations of Mesopotamia had no metals of their own, and must therefore have imported copper and tin. The copper may have come from Cyprus, while tin was perhaps obtained from the Khorasan district of Persia.

How the possibility of combining the two metals was first discovered is still a matter of dispute. Experts in the metallurgy of copper and tin are of the opinion that the original bronze founders could not possibly have produced bronze from accidental direct fusion of ores containing copper and tin. Ores containing both these metals are rare. It may be that tin was known as a separate metal almost as soon as copper, and that the evidence for a separate Copper Age, preceding the general use of bronze, is misleading. In their most primitive forms metal tools were of various flat types. Judging from the limited amount of chemical analysis which has so far been carried out, they appear to have been extensively made of copper only, thus supporting the Copper Age theory. But we know that to produce satisfactory results the casting of copper is most readily accomplished in flat moulds open to the air. The double, closed moulds used for the more complicated types of bronze casting produce unsatisfactory results in the case of copper. So that, especially if there was a shortage of tin at any time or in any locality, there would be a tendency to revert to the more primitive forms, using copper only.[1] All things considered, it is better to wait for the results of more detailed investigations before coming to any decision on this vexed question. For the present we will content ourselves with the knowledge that the use of both copper and tin spread steadily westward.

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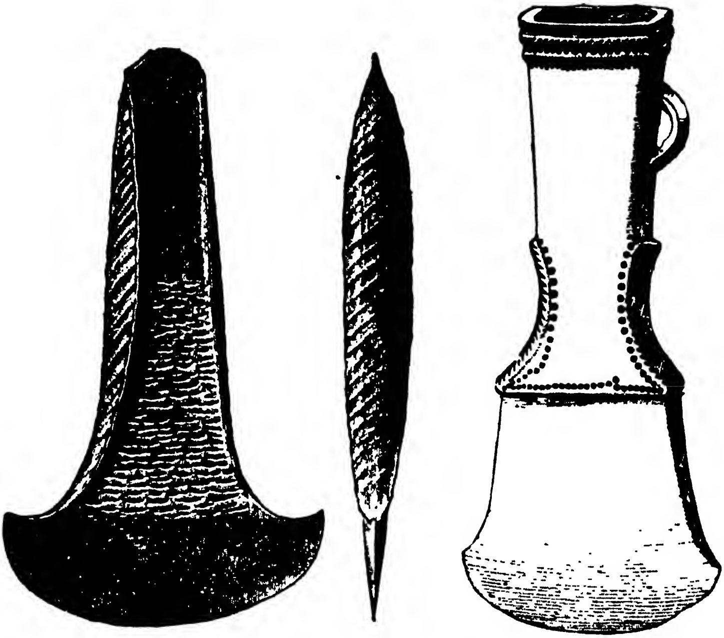
[1] All such dates are, of course, provisional. Much depends upon the views of the particular authorities consulted. The chronology used here is that which appears to be best supported by the evidence available.



(*Courtesy of the British Museum.*)

Bronze Age tools.

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[1] Note the widespread use of copper oxide to make the copper harder.—J. L. M.

By the time the copper mines of Elba and Etruria were being opened up, and the ore had been found in south-eastern Spain, while tin was being secured from Cornwall and the Scilly Islands, many hitherto Neolithic communities were well on the road to the Age of Metals. It was one of the most momentous stages in human progress, ranking with the discovery of fire, and that progressive control over the forces of Nature which is the distinctive feature of our own time. Nevertheless, man still had a long and toilsome road before him. He had acquired skill. He was learning to master metals. But he lacked science.

Primitive Bronze Founding

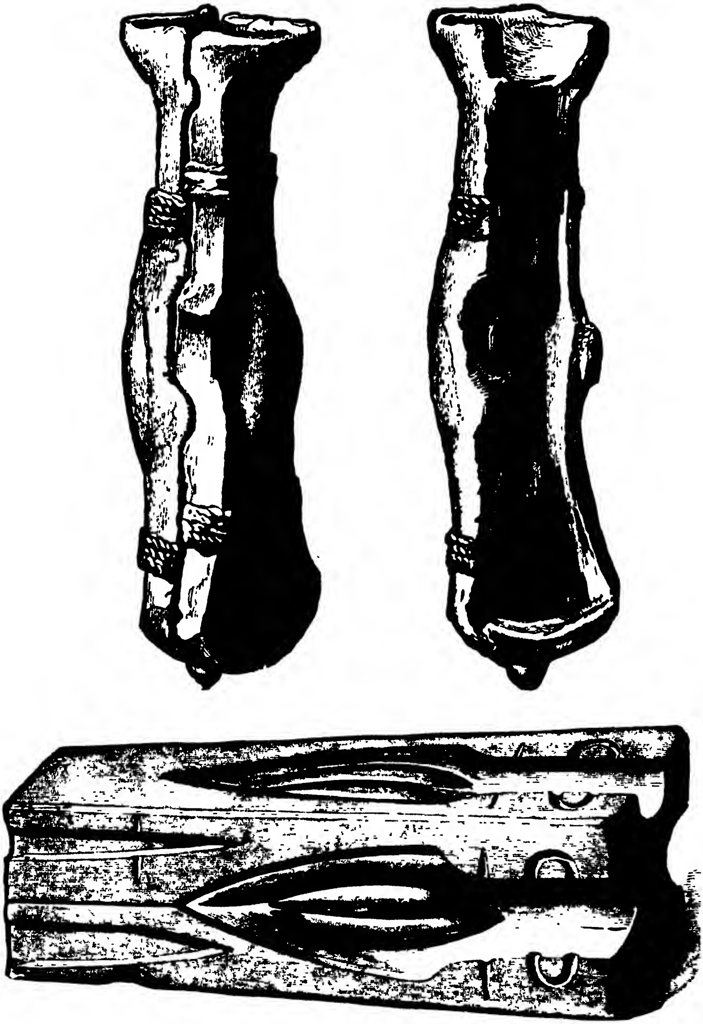
When at length knowledge of bronze and methods of working it reached western Europe we find the earliest tools much influenced in their shapes by previous experience in stone working. The flat "celt" for example can easily be matched by similar tools and weapons of flint. This, too, may be said of the copper and bronze daggers of this period, although the metal implements are thinner, indicating appreciation of new possibilities which were unattainable so long as flint was the only material available. Indeed, almost from the first such new possibilities must have been recognised, and advantage speedily taken of them. The result was a multitude of new forms, evolving in the first place out of the old, but soon adapted to a much greater variety of needs. Among these may be mentioned gouges, anvils, saws, files, tongs, punches, tweezers, sickles, and razors. All these are found in bronze; as are trumpets, bells, pins, bracelets, clasps, and a host of other tools, weapons, implements, and personal ornaments. Once the new metals were known they must have provided a wonderful outlet for man's long accumulated skill. Besides casting, the art was discovered late in the bronze period of hammering out metal into large and exceedingly thin sheets for the manufacture of cups and vessels. In whatever way the metal was drawn out, some of the specimens of this art are remarkable examples of dexterity in sheet metal working.

We are unable to throw much light on the earliest methods adopted for smelting, but small crucibles of burnt clay have been found, some of which had lumps of bronze still in them. Crucibles with and without handles have been discovered, and in all probability small ladles of earthenware were used for pouring out the metal.

Bronze has considerable fluidity when melted. This, together with its density and hardness and the small amount of contraction which takes place on solidifying, makes it very suitable for casting. The first process which appears to have been adopted after smelting the copper from the ore was to run it into a shallow concave mould. This was left open at the top. The metal then resembled an inverted cake, flat on top and convex below. These cakes were broken into numerous pieces before the metal had time to set, the small pieces being much better adapted for further casting than the large round slab would have been. Another method was to run the metal into long moulds, and it would appear that sand or clay was thrown in here and there so as to make the subsequent division of the ingot easier.

The next step was the actual moulding to some desired shape. This was done in various ways. Sometimes the metal was run into single open-top moulds formed of sand, loam, or stone. Where sand or loam was used a pattern would be required, which might be a metal object similar to that desired, or may have been made of wood. Another method involved the use of double moulds. Castings thus produced have been found in their unfinished state. Cores for producing hollow spaces in the castings soon came to be employed in conjunction with moulds of this type. A third method necessitated the use of a model of wax or some other substance which was readily combustible. This was encased in a mass of clay or loam, and, on being subjected to heat, the model would be melted or burnt out, leaving a cavity into which the molten metal could be poured while the mould was still hot.

The type of mould most commonly found in Great Britain is that made of stone. When of the closed form, the halves are sometimes provided with dowel-like projections to ensure accurate alignment and to keep the parts in position.



(*Courtesy of the British Museum.*)

Bronze Age moulds for casting.

Some moulds discovered in the remains of ancient dwellings on the Lake of Bienne and elsewhere, together with a considerable number of other items in the plant of some prehistoric bronze founder, may be mentioned here. The mould for a chisel is very nearly cylindrical. There is a funnel opening at one end, from which two holes lead to the interior of the mould, which is made of clay. The clay between the holes forms part of a conical core. Other moulds are of stone. What seems to be practically the whole stock-in-trade of another prehistoric bronze founder was discovered in the Isle of Harty, Kent. This includes a punch or pricker, moulds, cores, and socketed tools of various descriptions. Other items typical of the founder's art are the heads and runners, jets and other waste pieces which were collected and saved for re-melting. Frequently they show the shape of the funnel into which the metal was poured. In one instance no less than fifteen of these objects were found, six with one runner, three with two, and six with four.

After the castings were made it appears to have been fairly common practice in the case of flat objects like celts to subject them to a hammering process. Bronze hammers have been found, and also anvils made of this alloy. The former are plentiful, but the latter rare. No doubt a flat stone served as an anvil in many instances, and it is noteworthy that such " anvils " are still in use among native ironworkers of Africa, and until recently were not unknown among the country smiths and tinkers of Ireland. The bronze anvil was sometimes made for use in either of two positions, one or other of the pointed ends being driven into the smith's bench as required. Not only were plain surfaces provided, but also grooves suitable for a variety of swaging processes. There is in some of these anvils a higher percentage of tin than usual, thus ensuring a harder bronze.

The edges of tools which were to be sharpened were first drawn down by hammering, a process which at the same time rendered the metal more compact. In the case of socketed castings, hammering would also no doubt loosen the core, making it a simple matter to clear out the socket with pointed tools of the kind which have been discovered in many of the ancient bronze founders' hoards. Filing might precede hammering or follow it, and prehistoric files of bronze have been found in some of the lake-dwelling deposits. In the earliest form the serrations are very coarse, and are at right angles to the length of the blade. The files are from 5 to 10 inches long.

Finally, the surface of many tools was polished. This may have been done with sand, or on a grit rubbing-stone. Whetstones are not infrequently found in company with bronze implements.

Although the tool would now be in a finished state, the prehistoric worker was in many cases not satisfied until he had added some sort of ornamentation wherever a suitable surface was presented. For this purpose various types of punches were used, both chisel-ended and of the centre-punch variety. With these he was able to produce numerous conventional designs. In rather later stages of technique lines were made by an engraving process as well.

The development of prehistoric agricultural " engineering " is seen in improved types of bronze sickles. We have already referred to sickles of baked clay used by the earliest known inhabitants of Ur. It appears that sickles of wood, fitted with tiny flint teeth, were used in early Egyptian times, sickles of this type dating from about 2200 B.C. having been found. We know also that saws and sickles were made in this manner during the early Neolithic period. As soon as bronze passed into common use, however, we find sickles made of this metal, with a much better cutting edge, and formed with sockets for securing them to wooden handles. A pinhole in the socket provided means for fixing the handle, in the manner customary with modern hoes and suchlike tools.

Summing up, we may say that not much later than 2000 B.C. in Europe, and earlier in western Asia, Egypt, Cyprus, and Crete, considerable experience had been gained in tin and copper smelting, copper and bronze founding (involving the use of moulds and cores), smithy work, planishing, and polishing.[1] Man knew how to make tools in ever-increasing variety to meet the diverse needs of his embryonic civilisation. His skill in cutting, transporting and erecting large blocks of stone is attested by examples of such workmanship which still exist in many parts of Europe. He had also learned how to build simple structures of wood. Although such structures might perhaps be considered as examples of primitive architecture rather than early steps in engineering, we have to remember that knowledge and skill gained by constructional experience of this type had definite and immediate reactions on man's engineering progress.

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[1] 2000 B.C. is rather early for Europe, except in the Mediterranean peninsular.—J. L. M.

CHAPTER III

THE CONTROL OF WATER

The Significance of Water [1]

We must now turn to other developments of the highest importance which were already taking place in Egypt and Mesopotamia—the beginnings of hydraulic engineering. But since water has played so intimate a part in human evolution in the past, and must assuredly continue to do so through all future time, we shall make no apology for first digressing briefly on the subject of water itself, before telling of man's early efforts to control its flow for irrigation purposes.

Whatever else man may do without, he cannot dispense with water. We may go further and say that life itself would instantaneously become a thing of the past were this all-pervasive compound eliminated from the earth and the atmosphere which surrounds it.

Consider for a moment some of the manifold ways in which water enters the very texture of life and its environment. It is the principal constituent of active living organisms, comprising for example 70 to 85 per cent. of fishes, about 85 per cent. of apples, 78 per cent. of potatoes, and 95 per cent. of the edible portion of lettuce. It is ingested by living organisms in greater amounts than all other substances combined. If there were no rains and fertilising dews, vegetation—and with it all animal existence—would cease. Of the total extent of the earth's surface the oceans make up about three-fourths ; while, if our globe were a perfect sphere, the water they contain would cover the whole surface to a depth of between two and three miles. On land, in addition to lakes and rivers, water is almost universally present in large quantities in the soil. Even the atmosphere in which we live is a huge aerial reservoir of water. And of all terrestrial agents none is so actively engaged in modifying the surface of the earth. Vast quantities of vapour ceaselessly rise from seas, rivers, lakes, and glaciers. It has been calculated that the amount of heat employed in evaporating water from 100 square kilometres of tropical ocean is equivalent to over 100,000,000 horse-power; and in greater or less degree this action is taking place all over the world. Ceaselessly this vapour is condensed and falls chiefly as rain; swelling brooks and rivers and returning thence to the sea. Hour by hour and age after age this process goes on, endlessly transforming the surface of the planet on which we live. Every year, according to one calculation, the rivers of the earth carry off in suspension nearly five thousand million tons of dissolved mineral matter, besides prodigious quantities of sediment.

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[1] We are indebted in this section to that very suggestive and interesting book, *The Fitness of the Environment*, by L. J. Henderson.

It is scarcely surprising, therefore, that Thales should have taught that water is the origin of all things, or that Pliny should have said that "this one element seemeth to rule and command all the rest."[1]

Though water can no longer be regarded as an element, the investigations of modern science have only served to make the importance of this substance more abundantly clear than ever. We know now far more than was ever known before about the part played by water in making the earth exceptionally well adapted to sustain life. Owing to its high specific heat it tends to maintain oceans, lakes, and streams at a nearly constant temperature. The high specific heat of water also plays an important part in the formation and duration of ocean currents, and the amount of heat carried by such currents. It is responsible for the promotion of winds, and therefore the distribution of aqueous vapour throughout the atmosphere. Similarly it can be shown that many other properties which water possesses to a very unusual degree—its solvent and ionisation powers, surface tension, high latent heat of evaporation, high melting point compared with that of any similar substance, property of expansion on cooling near the freezing point, are all extraordinarily favourable to the perpetuation of life.

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[1] Thales thought water was the ἀρχή (origin, first cause), because all growth and change in his experience depended on the presence of water: dry seeds in dry soil do not grow; dry air yields no dew or rain; and so forth.—J. L. M.

Many other interesting facts about water might be quoted, but enough has already been said to indicate the highly significant *rôle* it plays in the evolution of all living things. We must proceed to note some of the especially important reactions of water on the trend of man's material progress from Neolithic times onward. The vessels which he made to contain it ; his canals, embankments, dams and other constructions for controlling its flow ; the wells he sank to obtain supplies of it ; the endless appliances he devised for raising it ; the cisterns he made in which to store it ; the bridges he built for crossing it ; and, finally, the ships he constructed to sail upon it ; all these were collectively of cardinal importance in developing his skill, ingenuity and inventive ability.

The Waters of the Nile

Particularly in hot countries subject to sudden and prolonged drought would man be stimulated to devise ways and means of gaining access to water, storing it and diverting it for drinking and irrigation purposes. So severe have these droughts been from time immemorial that the ancient literatures of the East abound with references to the sufferings of the people at such times. " The poor and the needy seek water, and there is none, and their tongue faileth for thirst." [1] And again : " The smith with the tongs . . . is hungry and his strength faileth, he drinketh no water, and is faint." [2] Even in lands adjacent to great rivers widespread distress might be occasioned by seasonal and other irregularities in the flow ; too little causing a famine, too much being followed by devastation and pestilence. Civilisation under these circumstances

[1] *Isaiah*, xli. 17.
[2] *Isaiah*, xliv. 12.

only became possible when determined efforts were made to regularise the flow, and to distribute the water in suitable quantity as, when, and where required. So we find that the earliest civilisations of which we have written records were founded on the control of water; and with the relaxation of that control their glory passed away. Not until well into the 19th and 20th centuries of our present era do we find anything to equal the degree of control achieved in Egypt in ages long gone by. So able, indeed, were the irrigation pioneers of ancient Egypt, that when Sir William Willcocks, designer of the great Assuan Dam, realised what they had accomplished several thousand years ago, he was impelled to refer to them as "giants in hydraulic engineering . . . as wise as they were courageous." [1]

It will be interesting to examine some of the evidence on which this remark was based, but before doing so we will endeavour to form a mental picture of the land itself, and of the great river which dominates it. To this end we cannot do better than quote the striking description of Egypt and the Nile given by Winwood Reade in *The Martyrdom of Man*:—

> "The land of Egypt is six hundred miles long, and is bounded by two ranges of naked limestone hills, which sometimes approach, and sometimes retire from, each other; leaving between them an average breadth of seven miles. On the north they widen and disappear, giving place to a marshy meadow plain which extends to the Mediterranean Coast. On the south they are no longer of limestone, but of granite; they narrow to a point; they close in till they almost touch; and through the mountain gate thus formed the river Nile leaps with a roar into the valley, and runs due north towards the sea.
>
> "In the winter and spring it rolls, a languid stream, through a dry and dusty plain. But in the summer an extraordinary thing happens. The river grows troubled and swift; it turns red as blood, and then green; it rises, it swells, till at length, overflowing its banks, it covers the adjoining lands to the base of the hills on either side. The whole valley becomes a lake, from which the villages rise like islands, for they are built on artificial mounds. . . .
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> "Far, far away in the distant regions of the south, in the deep heart of Africa, lie two inland seas. These are the head waters

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[1] Willcocks, *From the Garden of Eden to the Crossing of the Jordan.*

of the Nile ; its sources are in the sky. The existence of the Nile is due to the Nyanza Lakes alone, but the inundation of the river has a distinct and separate cause. In this phenomenon the lakes are not concerned.

" Between the Nile and the mouth of the Arabian Gulf are situated the highlands of Abyssinia, rising many thousand feet above the level of the sea, and intercepting the clouds of the Indian Ocean in their flight toward the north. From these mountains, as soon as the rainy season has set in, two great rivers come thundering down their dried-up beds, and rush into the Nile. The main stream is now forced impetuously along ; in the Nubian desert its swelling waters are held in between walls of rock ; as soon as it reaches the low-lying lands of Egypt it naturally overflows.

" The Abyssinian tributaries do ever more than this. The waters of the White Nile are transparent and pure ; but the Atbara and Blue Nile bring down from their native land a black silt, which the flood strews over the whole valley as a kind of top-dressing or manure. Thus, were it not for the White Nile, the Abyssinian rivers would be drunk up by the desert ; and were it not for the Abyssinian rivers, the White Nile would be a barren stream. The River is created by the rains of the equator : the Land by the tropical rains condensed in one spot by the Abyssinian mountain pile. . . .

" At the time we speak of, Egypt was irrigated by the Nile in a natural, and therefore, imperfect manner. Certain tracts were overflooded, others were left completely dry. The valley was filled with people to the brim. When it was a good Nile, every ear of corn, every bunch of dates, every papyrus stalk and lotus root, was pre-engaged. There was no waste and no surplus store. But sometimes a bad Nile came. . . ."

Out of these imperfections of natural irrigation, producing a surplus of agricultural products one year and scarcity another, came that impetus to invent, devise, and circumvent, which produced the earliest known large-scale engineering works of ancient Egypt. Out of these imperfections, as we shall see later, also came the first beginnings of earth-measure or geometry, much preoccupation with astrology and computation, and the efflorescence of a great civilisation. For it was adversity which stimulated the wits of her people, setting them to secure that control of their environment which alone could raise them above a state of primitive barbarity.

3

Irrigation in Ancient Egypt

As we pass from prehistoric times in Egypt to the age of written records, we find the art of irrigation already in an advanced stage of development. To Mena, believed to have been first king of the First Dynasty (3400 B.C. ?) is attributed the great work of dividing the country up into a series of basins, with canals leading to those which were more remote from the river.[1] By means of this system it became possible to divert much of the precious, water-borne silt on to the land ; to distribute both water and alluvium over a large area ; to provide means of draining off excess water as the inundation level fell ; and to store considerable quantities of water during inundation for release during the time when the Nile was at a low ebb.

The whole country was cut up into oblongs by raising dykes, which varied from 12 to 20 feet in height. Specially high dykes were made along the river banks. By cutting through these, water could be admitted to the basins ; where the lie of the land did not permit of direct access, it was first taken through connecting canals. When the basins were filled the openings were blocked up again. There the water was allowed to stand for a month or so, depositing its invaluable burden of silt. Then as the flood level fell, the clear water was finally allowed to run off to the river again, leaving a vast expanse of mud behind. By November of each year the waters of the inundation had passed away, the mud began to cake, and, as soon as it would bear the weight of a man the sowing of crops began.

The work of making and maintaining the dykes, and of digging and clearing out the canals, indicates constructive and organising ability of no mean order, considering the remote period at which this work was first begun. No doubt unorganised and patchy attempts to control the inundation had been made long before the time of Mena ; but to that king we must give the credit, it seems, for extending the work on a national scale. To him also may in all probability be given the credit for first attempting storage of water in large volumes; as a connection between the Nile and what was known later as Lake Mœris was in existence in his time. But it was King Amenemhat III. of the Twelfth Dynasty who widened and deepened the canal and built a great dam, converting the reservoir begun by King Mena into a vast inland sea with an area of 700 square miles and a capacity of some fifty thousand million cubic metres. By turning the waters of the inundation into this lake a very high flood could be reduced to one of moderate dimensions; while the waters thus impounded were available for release during a season of drought, or as might be determined by other considerations.

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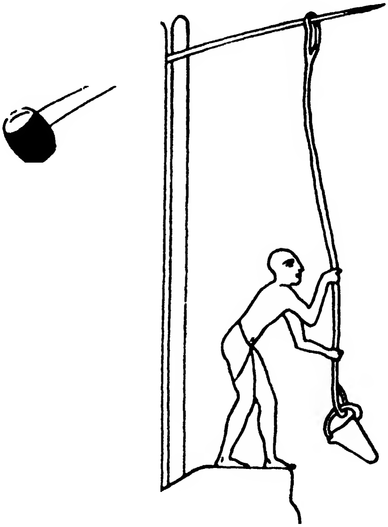
[1] On the mace-head of Nar-mer, another early ruler of the First Dynasty, the King is shown regulating the watercourses.—J. L. M.

Writing about 430 B.C., Herodotus described Lake Mœris as " manifestly an artificial excavation, for nearly in the centre there stands two pyramids, rising to the height of fifty fathoms above the surface of the water, and extending as far beneath, crowned each of them with a colossal statue sitting upon a throne. The water . . . is introduced by a canal from the Nile. The current sets for six months into the lake from the river, and for the next six months into the river from the lake."[1] Diodorus Siculus, writing about 24 B.C., remarked that the lake " is amazingly useful and incredibly large, for, as the rising of the Nile is irregular, and the fertility of the country depends on its uniformity, he (the king) dug the lake for the reception of the superfluous water, and he constructed a canal from the river to the lake 80 furlongs in length and 300 feet in breadth. Through this he admitted or let out the water as required." Strabo, who wrote a generation later than Diodorus, refers to " regulators at both ends for controlling the inflow and outflow."[2] There were large sluices and lock-gates in connection with the smaller works of the time, but the regulators to which Strabo refers appear to have been two earthen dams parallel to each other, closing the canal which connected Lake Mœris to the Nile. The upper regulator had a pyramid at its northern extremity, and here also was

[1] Herod. II, 149.
[2] Strabo, XVII, I, 37.

the famous Labyrinth, probably buildings and barracks used chiefly in connection with the military protection of the dam. The lower regulator, besides consisting of a massive earthen dam which was cut during dangerously high floods, also included a broad spill-way hewn out of solid rock. The level of this was adjusted for passing ordinary floods. The two dams were six miles apart. The irrigation of Lower Egypt, being effected by means of distributing canals, which previously had only received water during the high inundation period, was dependent on this great engineering work for an effective and prolonged distribution of water.[1]



An Egyptian *Shaduf.*

The level of the river had to be carefully watched. Although the inundation returned with almost clock-like regularity, reducing the work of dyke repairing, canal clearing, basin flooding, and crop sowing to a mechanical routine, yet there were variations from time to time which, as we have already indicated, might mean the calamity of excessive water, or, on the other hand, the equally dire disaster of drought. Water levels were therefore carefully recorded year after year from the time of Mena onward, the height of the inundation being measured by means of fixed meters at Elephantine, Thebes, Memphis and elsewhere. The ancient records show the heights to a fraction of an inch, so that the meters must have been fixed in still water. They consisted of a pillar or slab, standing in a well communicating freely with the river, the scale on the slab being divided into cubits and fractions of a cubit.

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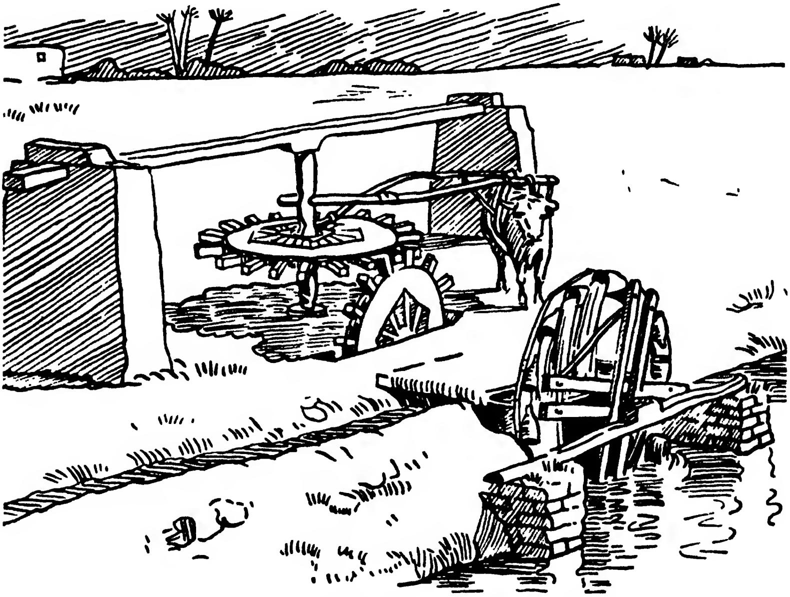
[1] Sir William Willcocks, *op. cit.*



Water-raising in Egypt, present day.

The Nile is deltaic ; that is to say, the land falls away gradually from the river banks. The lands bordering the river are seldom under water during normal floods, and when the floods are below normal the banks are never submerged. It is therefore necessary to irrigate such land by raising water artificially. This was and is still done by means of an apparatus now known as a *shaduf* or swape ; a device known to most civilised countries in all ages. Commonly it consists of a pole, pivoted about the centre between two upright posts, a bucket being attached by a cord to one end of the pole, and a counterpoise attached to the other end. The bucket is pulled down by hand, filled by dipping, and then raised to the height required by the help of the counterpoise. Sometimes these *shadufs* are arranged in relays, one feeding to another, when water has to be raised to an unusual height. It is just possible that some form of water-raising wheel, turned by bullocks and having a chain of buckets at the rim, was also known to the early Egyptians. There is, however, no evidence of this in ancient Egyptian records. The chain of pots for water raising was known to the Romans, and is described by Vitruvius ; but Professor Myres is inclined to believe that wheels of this type, as used in Egypt to-day, were probably derived from Persia and introduced to Egypt under Arab rule.

The people of ancient Egypt certainly never got beyond primitive water-raising appliances, nor did they—with the single exception of the Lake Mœris scheme—make any progress towards perennial irrigation. It was left to modern engineers to visualise and carry out projects ensuring perennial supplies of water to huge tracts of country in both Upper and Lower Egypt ; giving vastly increased security, yield, and diversity in the raising of crops.

4

Water Control in Babylonia

The irrigation requirements of early civilisations in Mesopotamia closely resembled those of ancient Egypt. The people were just as dependent upon periodical inundations, and without some effort to control and distribute the water thus provided the land would have been hopelessly sterile. For Babylonia lay in an almost rainless, sub-tropical zone, with scarcely 7 centimetres of rainfall in the whole year.

But it will be of interest to consider first some of the differences rather than resemblances between the two countries. A glance at a map will indicate that the Babylonians had special facilities for running water through canals, for they had two rivers to utilise and could make connections from one to the other. In this way a flow of water could be brought to points at a considerable distance from both the Tigris and the Euphrates. We should therefore expect to find the Babylonians skilled in the construction of canals, and this expectation is amply supported by archæological evidence and also evidence supplied by Greek and Roman historians.

Of the two rivers the Tigris is the more turbulent. For many months of the year the Euphrates shrinks to little more than a sluggish stream. But during the flood period it swells and covers its entire bed. Both rivers bring down the alluvial soil which is such an asset to the country. Indeed, the trouble in Mesopotamia is to avoid excess distribution of silt ; for there are no cataracts, and consequently no settlement of the coarser sediment occurs upstream. No doubt this was one of the reasons which led to hydraulic engineering being dealt with, almost from the first, by a public works department.

The earliest known inhabitants of Babylonia, the Sumerians, constructed canals in prehistoric times.[1] They also raised dykes and other earthworks, and even raised their towns on mounds, to ensure protection from the floods which followed the melting of snow on the great mountain ranges to the north-east. Once parched and barren, the land became at length so fruitful that Herodotus, writing of it in the 5th century B.C., remarks :—

> "Of all the countries that we know, there is none so fruitful in grain. . . . In grain it is so fruitful as to yield commonly two hundredfold, and when the production is greatest even three hundredfold. . . . As for the millet and the sesame, I shall not say to what height they grow, though within my own knowledge, for I am not ignorant that what I have already written concerning the fruitfulness of Babylonia, must seem incredible to those who have never visited the country." [2]

That this wonderful transformation was largely to the credit of the engineers of Sumer, Akkad, and, later, of Babylonia, we know, because with the passing of the irrigation system the land once more relapsed into the state of desert and marsh from which it is only now once more emerging with the application of modern engineering and skill.

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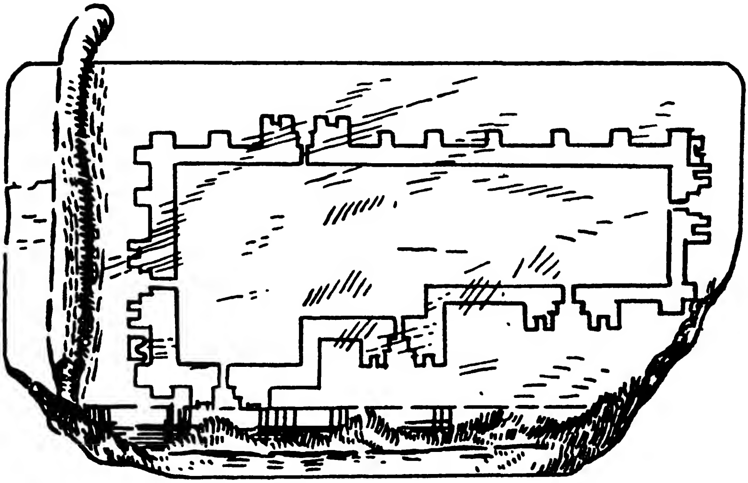
[1] Woolley's later excavations suggest that the Sumerians found the country already peopled with men of an earlier and different culture. The evidence will be found conveniently summarised in Peake, *The Flood*, 1930.—J. L. M.

[2] Herod. I, 193.

The ancient records are full of references to engineering achievements whereby the rivers were mastered and the country eventually turned into a paradise. When the first canals were constructed we do not know. Probably it was before the dawn of history. One of the earliest of which there is any record was dug at the command of Ur-Nina, who possibly flourished about 3000 B.C. Entemena, the great-grandson of Ur-Nina, constructed another canal "at the command of the goddess of irrigation" from the Tigris to the Euphrates south of Nippur. "The mighty canal, at the boundary of Enlil, Entemena made for Ningirsu." Both Entemena and his predecessor worked on the reservoir, which supplied the canal leading to the holy city of Nina, while at a later date another king, Urukagina, improved the canal



The earliest known "working drawing," about 2400 B.C. From a statue of Gudea, now in the Louvre.

system of Shirpurla. Later still, Sargon of Agade and his son, Naram-Sin, consolidated and greatly extended their territory, making and reconstructing canals, erecting great buildings, and improving the overland routes without which centralised control of an extensive kingdom would have been impossible. Gudea, Governor of Lagash, was another engineer-minded ruler who deepened and widened canals ; while for his structural work he imported materials from all the lands of south-western Asia, constructing roads to his quarries in the Lebanon, bringing timber from the Amanus Mountains and from Dilmun in the Persian Gulf, copper from northern Arabia, and dolerite from the Sinai peninsula. Reference should also be made to Khammurabi (about 1900 B.C.) if only for the light which the records of his time throw on the subject of early irrigation legislation. We learn from his famous Code, for example, that if a landowner caused damage to his neighbour's land by neglecting the banks of that portion of a canal for which he was responsible, he had to pay damages in full ; and if he were insolvent he could be sold up. But it is from the records of Nabopolassar (625–604 B.C.) and his son, Nebuchadnezzar II. (604–561 B.C.) that we get the most detailed descriptions of the artificial waterways on which the country was in their time dependent not only for irrigation, but for commercial and military defence purposes as well. Nabopolassar dug out the bed of the Euphrates from Babylon to Sippar and lined the banks with burnt brick and bitumen. He then enclosed Babylon with two moated walls, to which Nebuchadnezzar added a third. He also repaired the " Eastern Canal of Babylon," lined it with brick and bitumen, and built a bridge over it. Of his hydraulic engineering feats at Babylon he remarks :—

> " In order to strengthen the defences I heaped up great banks of earth about the sides of Babylon, and great floods of destroying waters like the great waves of the sea I made to flow about it. . . . That an enemy with evil intention might not press on the sides of Babylon, with much water like the floods of the sea I surrounded the land. That their waves might not make a break in them, as the surging of the bellowing sea, the bitter stream, a dam of earth I heaped up for them, and a moat wall of stone I placed around

them."[1] And finally: "The canal on the eastern side which a former king had caused to be dug, but whose channel he had not built, that canal I caused to be built, of bitumen and bricks I made its bed. *Waters that would never dry up in abundance I procured for the land.*"

Now from this and much other evidence of a similar nature it is clear that not only had a considerable measure of control over the Tigris and Euphrates been established, but, if the statement of Nebuchadnezzar, which we have italicised, can be taken literally, the problem of perennial irrigation, as distinct from control of the inundation, had been solved. In other words, it appears that the Babylonian engineers had secured results which have been widely held to be an entirely modern achievement. A consideration which adds support to this view is the fact that the flood season in Babylonia occurred six months later than in Egypt. Thus under natural conditions the summer arrived before the waters had receded; making ordinary flood irrigation on any extended scale a very imperfect process. Yet the quotations from Herodotus already cited indicate that the country as a whole was exceedingly fruitful.

Elsewhere in his history, Herodotus tells how Nitocris, a queen of Babylon, had an embankment made along each side of the Euphrates, wonderful for both breadth and height, and then dug a basin for a reservoir a great way above Babylon, close alongside the stream, and of such breadth that the whole circuit measured 420 furlongs. When the excavation was finished, she had stones brought, and with them bordered the entire margin of the reservoir. There are still to-day traces of a great dam above the site of Babylon. Sir William Willcocks, who has made a special study of the matter, has satisfied himself that the Babylonians did actually establish a system of perennial irrigation.

"The ancient Babylonians," he remarks, "controlled the Euphrates by means of powerful escapes into two depressions. . . . In ancient times these depressions were used not only as escapes for controlling the floods, but also as reservoirs for feeding the rivers in low supply. They were . . . rendered capable of accommodating six milliards of tons of water, of which about a quarter was utilised for feeding the rivers in the time of low supply. The Euphrates was thoroughly controlled."

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[1] *Building Inscriptions of the Neo-Babylonian Empire.*—Stephen Langdon, translated by E. M. Lamond.

And of the Tigris he says :—

" Some kilometres above the spot where the Tigris entered its delta the valley was barred by a massive earthen dam, and the river turned over a hard conglomerate, so that it could flow at a high level and irrigate the country on both banks. From the upstream side of the dam were taken the three heads of the great Nahrwan Canal." [1]

Much as we should like to discuss this highly interesting subject in greater detail, we cannot do so here. Our purpose, after all, is primarily to demonstrate how early civilised man was gradually attaining to greater mastery over materials, and was becoming accustomed to the idea of large-scale engineering enterprise, whilst still almost entirely dependent upon human muscles for his power supply.[2] This is a matter which can be illustrated by more than one type of activity, and we propose to turn next to some of man's striking structural achievements in the times we have just been considering.

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[1] The irrigation system was finally destroyed by the Mongols and Tartars in the 13th and 14th centuries A.D.

[2] It may be added that irrigation in pre-Roman times was by no means confined to Egypt and Mesopotamia. Darius established a great water-basin for this purpose in the district of Herat, in Persia, the outflow to surrounding districts being controlled by five gates. The Sabæans of south-west Arabia (who were also remarkably fine masons and stone-cutters) devoted much care to irrigation. Again, there is evidence that irrigation was practised in Seistan along the Helmund in very early times. So also in the neighbourhood of Damascus ; and other examples might be quoted. It is interesting to compare the irrigation methods of antiquity with those of the Incas of Peru, particulars of which will be found in Garcilaso'—*Royal Commentaries of Peru.*

CHAPTER IV

EARLY STRUCTURAL ACHIEVEMENT

The Great Pyramid

THE Great Pyramid had been described as "the most prodigious of all human constructions." It was built of some two million, three hundred thousand blocks of limestone, each weighing on an average 2½ tons, although the basement stones weigh from 46 to 57 tons. This means that stone having a total weight of about five million, seven hundred and fifty thousand tons was quarried, shaped, transported, and erected for the building of this vast structure ! Herodotus states that, according to the tradition of his time, one hundred thousand men were engaged on this work, moving the blocks during three months of each year. Many of the statements of Herodotus were for long received with incredulity, but the discoveries of archæologists in recent decades tend to confirm rather than to throw doubt on his accuracy. His accounts of the building of the Great Pyramid, according to Professor Petrie, fit the conditions so closely that we may believe they were correctly transmitted. The stone was quarried in the limestone hills between the river and the Gulf of Suez, to the south-west of the site now occupied by Cairo. The blocks were floated across the valley during periods of inundation, and then dragged up a specially prepared incline of polished stone three-quarters of a mile long and 60 feet wide. This causeway together with the preparation of the site—again according to Herodotus—took ten years to make, and in itself must have been a formidable task.

The base of the pyramid is some 755 feet square, covering an area equal to that of Lincoln's Inn Fields, London. Its original height was 480 feet. For comparison we may mention

(Courtesy of the British Museum.)

The Great Pyramid and the Sphinx before the clearance in 1926.

Salisbury Cathedral Spire (England), 404 feet, and the Capitol at Washington (U.S.A.), 307½ feet. The accuracy of the workmanship may be gauged from the fact that the average error in the base is less than one ten-thousandth of the side in equality, in squareness, and in level. There are 13 acres of finely jointed casing, fitted together with such exquisite attention to detail that many of the seams are almost invisible, and do not exceed in width one ten-thousandth part of an inch.[1]

The interior also affords amazing examples of workmanship, particularly that portion known as the "King's Chamber." This is a room 34 feet long, 17 feet wide, 19 feet high, constructed of huge granite blocks highly polished and fitted together with wonderful skill. Above the chamber, forming the roof, are nine blocks each about 19 feet long and 4 feet wide. Above these again is a series of low chambers, finally surmounted by great sloping blocks meeting at the apex and arranged so as to take the load of the enormous superincumbent mass. So well was the desired result achieved that after nearly fifty centuries have passed there is no sign of settlement, crack, or flaw, discernable.

Herodotus states that the highest parts of the pyramid were finished first. Professor Breasted, on the other hand, is of opinion that the upper portion was finished last; basing this view on the fact that the workmanship here shows signs of deterioration, as though built with greater haste than the lower sections. As to the method of building, Herodotus tells us that the Pyramid was first erected in the form of steps, after which the remaining pieces of stone were raised from step to step by means of "machines made of short pieces of wood."

In this way the men worked down from the top and "last of all they finished the parts on the ground that were lowest."

Many theories have been suggested to explain how this colossal bulk of masonry was raised into position. Though much may be done by a multitude of men working in unison under fear of the lash, it is incredible that the Great Pyramid was built without the aid of some mechanical lifting device. What were the " machines made of short pieces of wood " mentioned by Herodotus ?

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[1] This workmanship was equalled in a later age, if not excelled, by the Incas of Peru in their stone structures at Cusco and elsewhere.

One of the most plausible suggestions is that they were built on the principle of the *shaduf*.[1] A strong beam pivoted at the centre, with a rope sling for holding blocks of stone at one end and a rope basket at the other, into which weights could be placed, would certainly form a primitive kind of crane ; and in default of a better might be used with considerable effect. At a much later date a similar device appears to have been used by Archimedes, who, indeed, was possibly indebted to Egypt for several of the inventions attributed to him, including the screw for raising water. It is related that when the Roman vessels, at the siege of Syracuse, were grappled by the hooks and levers arranged by Archimedes to project over the walls of the city, their resemblance to vessels of water raised by a *shaduf* was so striking that Marcellus was afterwards wont to remark that Archimedes used his ships " to draw water with."

But even supposing that the pyramid builders used such elementary cranes, it is still difficult to understand how they were able to move heavy blocks in the confined spaces in which they must frequently have been placed. Possibly a rough form of screw jack was used. It is at least significant in this connection that the invention of both the screw press and the hydraulic press has been attributed to Greeks who spent much of their time in Egypt.

While the organisation of human skill, ingenuity, and labour on such a vast scale must in one sense be considered a tragic waste of the capacity and resources of a nation, yet from another point of view we may regard it as having provided invaluable experience in co-operative effort, the lesson of which would not be altogether lost to later generations. Labourers and slaves must have been organised into gangs working under the supervision of foremen and engineers, the collective energies of such men being focussed on ends which would have remained for ever unattainable so long as each individual had continued to work for himself alone. Planning the Great Pyramid; making all arrangements; providing for emergencies and accidents; organising the transport, commissariat, water supply, and other facilities; disposing the available labour to the best advantage; must have called for a degree of intelligence and co-ordination of effort probably unprecedented in the world's history.

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[1] See *Mechanical Triumphs of the Ancient Egyptians*, by F. M. Barber (Kegan Paul).

We shall not lay special stress on the almost incredible amount of straining man-power used in building this and the other pyramids of Egypt, the years of heavy, wearisome and unrequited toil exacted from the people, the tragedy of stunted, wasted lives. After all, such or little better was the lot of countless millions all over the earth until the use of external power brought with it the hope of amelioration for all mankind.

Obelisk Engineering

The engineering skill of the inhabitants of ancient Egypt is further illustrated by those enormous monolithic pillars, known as obelisks, which they erected in various parts of their country. The problem of how these obelisks—each cut in one piece out of granite, and some of them over 100 feet high—were quarried, transported and erected, has been studied in considerable detail by Mr. R. Engelbach, who brings to the task both experience in Egyptology and the training of an engineer. In this section we have followed his guidance very closely, and to his books on the subject readers desiring fuller information are referred.[1]

Obelisks, of weights up to 500 tons each, must formerly have been a common feature in association with Egyptian architecture. Only five now remain standing in the country of their origin, though several have been removed and re-erected in other lands. One now stands on the Thames Embankment, London, and another in Central Park, New York. Others are in Rome, Paris, and Constantinople. The craze for this particular form of vandalism has fortunately subsided in recent years.

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[1] *The Problem of the Obelisks* and *The Asswan Obelisk.*

There still lies in the quarries at Asswan a block of granite estimated to weigh 1,168 tons, which was intended for what might be termed a super-obelisk, but was left there unfinished, owing to an unexpected fissure in the rock. The methods adopted by ancient engineers for cutting, splitting, and shaping the granite can still be studied at the quarries. The marks of their wedges and chisels are clearly visible, as also are the lines made in marking out the work; and a record of measuring tallies may be seen on the quarry face. After a fissure in the granite made the engineers abandon their original project, the block was marked off afresh for cutting out a smaller obelisk, but this task was also abandoned after what must have amounted altogether to months of wearying work and anxiety.

The first step after the location of a suitable piece of rock would be to mark a centre line on the surface of the proposed obelisk. This was probably done by the method familiar to engineers of stretching a string covered with "reddle" and allowing it to touch the stone when correctly placed. A pot containing red ochre was actually found near this obelisk. From this line measurements would be made, and the outline of the obelisk scribed on the stone with a metal tool. Trenches were then made down each side. These were not cut but *bashed* out with balls or "pounders" of dolerite, many hundreds of which have been found in the quarry. These balls measure from 5 to 12 inches in diameter and weigh on the average 12 lbs. They may have been mounted on shafts, as some of them have been split in two, a feat practically impossible so long as they are only held in the hand. That these balls were used for pounding out the rock is clear from the nature of the trenches which, as Mr. Engelbach puts it, look as though they had been dug out with a gigantic cheese scoop.

The surface of the obelisk was also trimmed up entirely by means of these dolerite balls. Small boning-rods used by the ancient Egyptians have been found, and it is probable that a similar but larger scale device was used for obtaining a flat surface on the rock. Boning-rods may be seen in use to-day among builders and road makers, one rod being held up at each end of the surface it is required to level, and a third being held in between. By sighting across the top of the three rods, inequalities in the surface can be detected.

Iron chisels and wedges may have been used in connection with such work, but there is no certainty in the matter, though an iron wedge was found in the Great Pyramid.[1] We know that razors of the time were made of copper, and, since copper with 2 per cent. alloy can be rendered by hammering as hard as mild steel, it may be that this was the metal in general use in connection with the obelisks. We know also that the Egyptians drilled and cut the toughest kinds of stone with tubular drills of reed ; bronze tools set with cutting points, probably of corundum ; and long copper saws which, like the drills, were reinforced by sand and emery.

The method of erecting an obelisk is also a matter concerning which we have no definite information. Several methods have been suggested, but by far the most probable is that indicated by Mr. Engelbach. This method, already briefly alluded to in connection with Stonehenge, would involve building a ramp of earth, probably faced with stone, up which the obelisk would have been hauled on a sledge. There would be a tapering, funnel-shaped pit formed in the embankment at the spot where the obelisk was to stand. This would be filled with sand, on to which the obelisk would be tipped on reaching the top of the ramp. As the sand was removed the obelisk would settle down, being guided approximately into position by the converging sides of the pit. A guiding notch was provided on the pedestals on which obelisks were to stand, and once the obelisk was registered on this it would not be very difficult to pull it into an upright position. Thereafter the whole of the earthen embankment would be cut away and the job generally " squared off."

Mr. Engelbach points out that it would be necessary for the obelisk to be of such proportions that when supported at or pivoting round its balancing point, it would not break under the stresses set up by its own weight. The knowledge of the Egyptians was, of course, purely empirical in matters of this sort ; but in *The Asswan Obelisk* Mr. Engelbach makes lengthy calculations to show that this great slab of granite could be supported anywhere without stressing the material to more than two-thirds of what it could readily stand. This, of course, is on the assumption that the granite was flawless.

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[1] See p. 83.

It has taxed modern ingenuity to the utmost to remove and re-erect some of these obelisks, in spite of several thousand years of technological experience and knowledge gained by mankind since they were made. Yet Egyptian engineers in those far-off times made and erected a large number of these megalithic monuments, and apparently regarded such feats as being so commonplace as to make it not worth while recording how they did it.

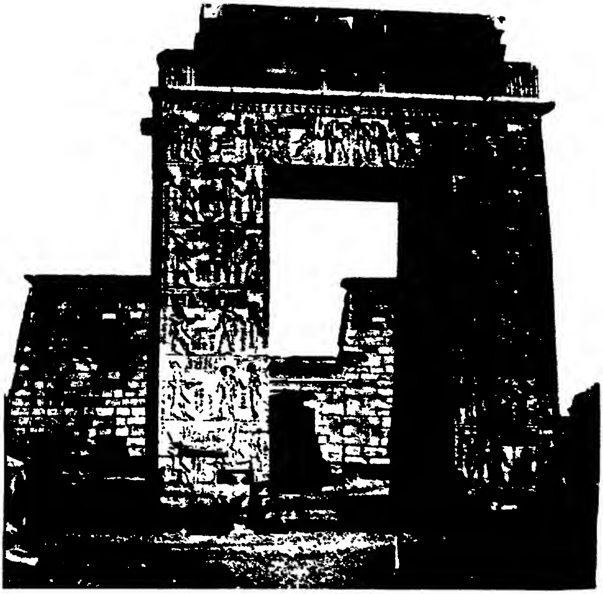
3

Ancient Egyptian Masonry

One Pharaoh after another vied with his predecessors in the scale and magnificence of his building activities. Temples in particular were built of huge proportions and of a solidity in construction which was calculated to withstand the ravages of time. One of the most impressive of such works was the great pillared hall at Karnak.

The temple at Karnak is a collection of buildings rather than a single edifice. Altered and added to from time to time in accordance with the religious zeal or the royal whim of the moment, it presents as a whole a disconcerting effect of incoherence ; for which, however, the marvellous execution of the various parts goes far to compensate. All writers agree in praising the great hall of this temple. Rawlinson refers to it as the most splendid single chamber that has ever been built. Breasted, in glowing terms, remarks that :

> " He who stands for the first time in the shadow of its overwhelming colonnades, that forest of mighty shafts, the largest ever erected by human hands, crowned by the swelling capitals of the nave, on each of which a hundred men may stand together,—he who



(*Courtesy of the British Museum.*)

Gateway of Ptolemy IX at Karnak.

To face p. 58.

Courtesy of the British Museum.

Statues of Amenhetep III. 1400 B.C. The statue on the right is the "Colossus of Memnon."

observes the vast sweep of its aisles, roofed with hundred-ton architraves, and knows that its walls would contain the entire cathedral of Notre Dame and leave plenty of room to spare—he who notes the colossal portal over which once lay a lintel block over forty feet long and weighing some hundred and fifty tons, will be filled with respect for the age that produced this stupendous colonnaded hall." [1]

A large part of this building was undertaken by Seti I. (about 1320 B.C.), who added to it seventy-nine of the great columns. Seti was evidently a man of large and sumptuous ideas, for he also caused a tomb nearly 350 feet long to be hewn out for him in the Valley of the Tombs of the Kings. One of Seti's predecessors, Amenhetep III., had already set an example in masonry work on a scale never previously known. Among the remarkable works of this king were two great sandstone statues of himself, each about 60 feet high. According to legend, one of these statues, known as the "Colossus of Memnon," is said to have emitted a sweet, sad note daily just after sunrise. After the statue was damaged by an earthquake in 27 B.C. the sound was no longer heard. Heron of Alexandria, in his *Pneumatics*, describes devices which, in conjunction with the heat of the sun's rays, might have been used to produce the sound in question.

But though one of the most notable features of Egyptian workmanship in stone is the astonishing size of many buildings and statues, it is not to be supposed that the Egyptians carried out all such work on a large scale. Nor did they always think it necessary that their stone blocks should be big if they were to be impressive. Generally, the size of blocks used in building is very much what we should ourselves use at the present day.

The materials varied considerably, and were sometimes brought into association in a way that did not enhance the architectural effect. Limestone, sandstone, granite, and alabaster were all used. Thick walls were built of a core of rough blocks piled together, and then faced with casing stones carefully finished off on all sides except the back, which was roughened to hold the mortar—that is, in those periods when mortar was used. No great depth of foundation work was considered necessary, the soil of the Nile valley being so hard and compact as to be almost incompressible. The wall stones were sometimes laid together without any binding material, the weight being relied upon to keep the building intact. In other places metal cramps of copper or lead were used, and sometimes a mortar of lime and sand with perhaps an admixture of brick dust. Maspero tells us that where the edges or corners were broken away, the workmen would, in order to avoid waste, insert pieces of stone. If the stone was too short, or not high enough, a supplementary slab was inserted. It appears that the adoption of such expedients led to careless ways of working. " The masons who had inadvertently drawn up too large a block did not trouble to hew it again, but adjusted it by one of the expedients just mentioned." Insufficient supervision was given to the laying of blocks, so that vertical joints came over each other for two or three courses. Scamped work was not infrequently covered over with a coating of cement or stucco.

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[1] Breasted, *History of Egypt*. 2nd ed. p. 450.

It is often asserted that the Egyptians must have been familiar with steel, or that they had some way of hardening copper, the secret of which is now lost. Otherwise, it is argued, how could they have shaped such prodigious quantities of stone, much of it so hard that even to-day the working of it would not be easy? But Maspero supplies a convincing explanation ; telling us that the various manufacturers of " antiquities " who work granite for the benefit of tourists have solved the matter. These men work with twenty or more points and chisels of inferior iron, which are rendered unusable by a few blows.

> " The first one spoilt, they take another, and so on, until their store is exhausted, when they take the whole collection to the forge to be put to rights. The proceeding is neither so slow nor so difficult as might be imagined. There is now in the Cairo Museum a life-size head which was produced by one of the best forgers in Luxor in less than a fortnight from a block of black granite streaked with red." [1]

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[1] Maspero, *Manual of Egyptian Archæology*, p. 222.

Quarrying was carried on whenever good stone was available. Sandstone quarries consisted of open pits, but most of the limestone was obtained from galleries cut into the face of cliffs. First a number of these galleries were driven parallel to each other, and then these were joined by cross galleries, pillars being left in between to support the roof and superincumbent rock. Oxen were often used for dragging the sledges on which stone was transported, asses for carrying supplies of food and water. Sometimes the men working at the quarries were well looked after. Seti I. in particular appears to have treated those who were his own people with unusual consideration, his records showing that at the Silsileh quarries each of the thousand men employed there received daily nearly 4 lbs. of bread, two bundles of vegetables and a roast of meat, while twice a month each man was given a clean garment. It must be admitted, however, that such treatment was not general. Unceasing labour, accompanied by periods of semi-starvation and neglect, was much more customary ; not only at the quarries, but among the common people everywhere.

It is quite clear that in those days, and for many centuries afterwards, there was little leisure and less entertainment for manual workers, whatever their occupation, while their home conditions were in many respects but little removed from a level of barbarism. In Egypt their houses were mere hovels of mud, with one hole to serve as door and another—higher up—to let out the acrid smoke of their fires. In the towns, of course, there were houses of a very different order, the occupants of which probably found life pleasant enough in many respects. In Babylonia, too, there were cities which must have afforded to some at least of their inhabitants the possibility of a comfortable and cultured existence. First among such cities was Babylon itself; and as this metropolis eventually reached quite amazing proportions, and a magnificence which left it without a rival for centuries, a description of it as it was at the height of its glory will serve to illustrate further interesting aspects of man's early structural achievement.

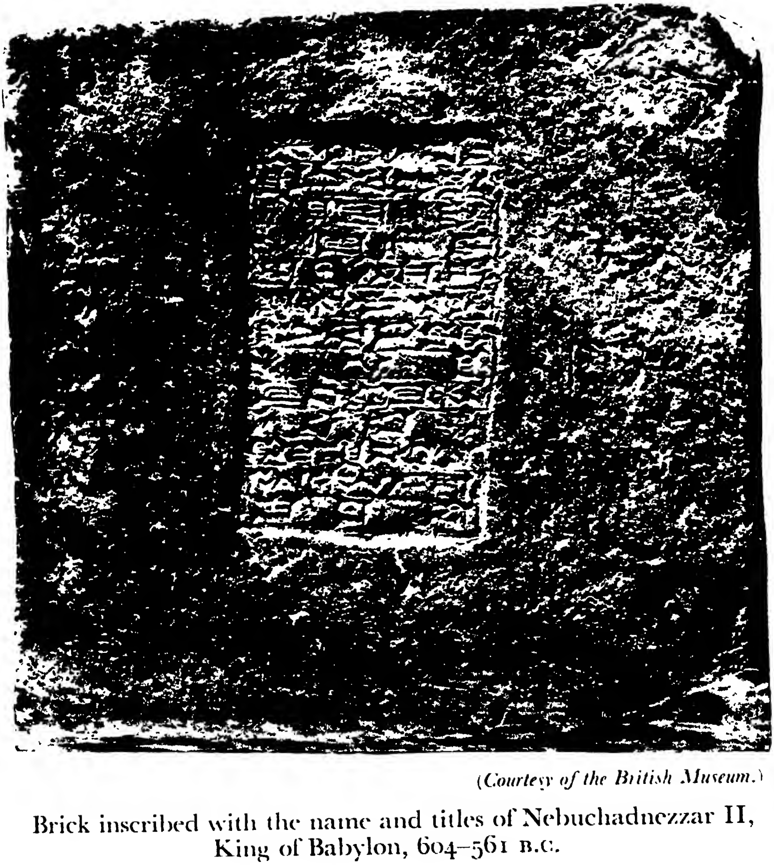
4

The City of Shining Gates

Babylon, once known also as the Gate of God and the City of Shining Gates, had its origins in prehistoric times. After a long and chequered career it was destroyed by the Assyrian, Sennacherib, who came down on the city " like a wolf on the fold " in 689 B.C. His successor, Esarhaddon, rebuilt Babylon and took steps to restore its ancient privileges and prosperity. After him Nabopolassar and his son, Nebuchadnezzar, made the new city more splendid than ever. " Babylon I made glorious that men might behold " writes Nebuchadnezzar exultantly, and we shall have occasion to note that his claim was justified. We have already referred to the hydraulic engineering activities of these remarkable rulers. Now we shall see the manner of their accomplishments in structural engineering.

We have several sources of information about Babylon. Lengthy descriptions of the city are to be found in the works of Greek and Roman writers, many Babylonian and Assyrian records have been recovered and translated, whilst archæologists have disinterred remains of the city itself.

According to Herodotus, the new Babylon occupied an area of about 100 square miles. Nebuchadnezzar built great encircling walls, surmounted with 250 towers which rose 300 feet above the plain. A road along the top of these walls was wide enough to allow a four-horse chariot to turn. Strabo, in his Geography, goes further and says that chariots with four horses when they met could pass each other with ease. In the walls were 100 gates of cedar, faced with polished bronze. Nebuchadnezzar, in his own account, says that he built a massive wall as high as a mountain, dug its moat, built a protecting bank made of bricks bound together with bitumen, and made quay-walls of burnt brick. Within the walls were the great palaces, the temples, and the houses " four and five storeys high " in streets which ran down to the water edge. The two parts of the city were joined together by a bridge, constructed of burnt brick, stone, and timber, at the west end



(*Courtesy of the British Museum.*)

Brick inscribed with the name and titles of Nebuchadnezzar II, King of Babylon, 604–561 B.C.

of what was known as the Street of the Procession. Seven river piers of the bridge have been excavated. Its length was probably about 230 feet. The piers are built with a very marked batter, the sides being convex and meeting in a point facing the current on the north.

The Procession Street was paved with slabs of limestone, 3 feet 6 inches square, laid on a foundation of bricks covered with asphalt. The whole of this part of the city was magnificent in the extreme, the street being flanked by walls on which were representations of 120 snarling lions finished with a brilliant enamel.

Enamelled tiles, arresting representations of animals, vast and richly decorated buildings, the temple of Marduk glittering with gold and silver and precious stones, a great tower surmounted by a golden image of the god Bel-Marduk, besides other objects of the same precious material, all attested to the magnificence of this amazing metropolis, of which the ruins still fill visitors with wonder after the lapse of over twenty centuries. Within the precincts of Nebuchadnezzar's palace rose the famous Hanging Gardens ; terraced 75 feet high, and watered by means of some sort of machinery, which may have been an endless chain of buckets. Koldewey tells us in his *Excavations at Babylon* that the southern citadel or palace contains a well with three shafts that must have enclosed this mechanism, which went down from the highest terrace to the level of the Euphrates.

Some idea of the great size of Babylon may be obtained from the statement of Herodotus that when Cyrus the Persian attacked the city and gained access to it by diverting the river, the inhabitants of the central parts, long after the outer portions of the town were taken, knew nothing of what had happened ; but, being engaged in a festival, continued dancing and revelling until news of the capture at length reached them. Further confirmation of this is to be found in the Old Testament, where Jeremiah states that " one post shall run to meet another, and one messenger to meet another, to show the king of Babylon that his city is taken at one end."

It must not be inferred that space within the ramparts was entirely filled with streets. No doubt there were districts ploughed and sown so that in case of a siege the inhabitants might be fed by the city's own produce.

At some distance from the outer ramparts there was an inner wall, protected by a moat, and having a strong fort at its northern angle. This wall and moat encircled the inner city, and within that again was the citadel containing the palaces of the king, the temples, and houses of the nobles and others attached to the king's retinue.

Diodorus Siculus records that in addition to the bridge there was a tunnel under the Euphrates at Babylon, cased with bricks and coated with bitumen. The passage way is said to have been 15 feet wide and 12 feet high to the spring of the vault.[1] Though no trace of this tunnel has yet been discovered, there is nothing incredible in the statement that such a tunnel once existed. Vaulting composed of contiguous rings of true arching had at the time of Nebuchadnezzar already been known for several thousand years ; the earliest known examples, in the royal tombs discovered at Ur, dating back to before 3000 B.C., according to current computation. Corbelled arches were no doubt known even earlier still. Moreover, tunnel work on a far larger scale was undertaken by many early engineers. A tunnel near Naples was regarded as prehistoric, even by men writing 2,000 years ago. It is 2,316 feet long, 22 feet wide, and has an average height of 89 feet. The celebrated Greek engineer, Eupalinus, who flourished in the 6th century B.C., carried out successfully several large-scale water supply undertakings. One of these involved cutting a tunnel 8 feet square and 4,240 feet long through a hill which rose between the town of Samos and the source of supply.[2] This tunnel, driven about 530–520 B.C., was cut from both ends, in hard limestone, on the level, and meets with only a yard of error. It must have been surveyed over the ridge, which is a couple of hundred feet at least above the tunnel.

Another tunnel, leading from the Lacus Fucinus to the Liris, is a striking example of what could be done by Roman engineers.

[1] Diod. Sic. II, ix, 2.

[2] Herodotus, III, 60.

Conceived by Julius Cæsar, and executed by Claudius, it passed for more than a mile under a mountain whose summit is over 1,000 feet above the level of the lake. The tunnel was driven for more than a mile and a half through rock so hard that every inch had to be worked with the chisel. According to Suetonius, this work occupied 30,000 men continuously for eleven years.[1]

Digressing a little further on this interesting subject, we may note that early tunnel engineers sometimes made mistakes which led to difficulties. In 2 Kings xx, 20, we are told that Hezekiah improved the water supplies of Jerusalem by making a pool, and conduit or tunnel. This tunnel through the rock, from Gihon to Siloam, still exists ; and there is an inscription at one end in ancient Hebrew characters which tells how there was an error in the reckoning, the men who worked from each end failing to meet at the middle in the same straight line. As they approached, however, the two parties called out one to the other, and corrected the error by hewing a cross-cut at right angles to the main line of the tunnel. The accuracy of this record has been confirmed by engineering surveys of the tunnel in recent years.

Returning now to our main subject, we may note that for structural work Babylon lacked the stone so plentiful in the quarries of Egypt. It was in great demand, but for the most part her people had to be content with brick. Nevertheless, kings and princes had ways of satisfying their desires, and expeditions were sent far afield for alabaster, dolerite, diorite, basalt, granite and other kinds of stone. The black basalt of Armenia was largely used. It could be floated down the river on rafts buoyed up by inflated skins, such as are still used in that land at the present day.

5

Early Sanitary Engineering

It has been said that the real test of a people's material progress is not the magnificence of their buildings, nor the splendour of their decorative arts, but the degree of perfection they have reached in sanitary engineering. If that is true—and certainly the statement contains a large element of truth—then it is to be feared that few civilisations of antiquity if put to this test would make much of a showing. Judged by modern civilised standards, even " the glory that was Greece " had a very unsavoury basis in this regard. The Greeks were not personally a clean race, while if we may judge from the state of affairs in Athens, even in her palmiest days, their sanitary arrangements were deplorable. Athens, says Mr. Alfred Zimmern in his book *The Greek Commonwealth*, " had no sewers, or even cesspools, and over the whole department of sanitation it is best to draw a veil."

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[1] Pliny, *Natural History*, XXXVI, 24. Suetonius, *History of the Twelve Cæsars*, Claud. 20. Tacitus, *Annals*, XII, 56.

It is all the more surprising, therefore, to learn that civilisations which flourished centuries before Greece figured conspicuously in world affairs had reached relatively high levels of both public and private sanitation. Two of the most striking examples are afforded by the Minoans of Crete, and the peoples of western India, whose buried civilisation is now being disinterred.

While the Egyptians were still adding to the massive structures which have astonished mankind ever since, the Minoans were developing a civilisation on different lines, with Crete as a centre. For long this people was regarded as purely legendary. Now we know that the king Minos of Greek fable was an individual, or series of individuals, who had really existed, and that the place where he lived was the palace of Knossos in Crete.

This palace was a vast building which, no doubt, accommodated a great number of the king's subjects in addition to his courtiers and personal attendants. The scale on which the palace was built may be gathered from the dimensions of the grand staircase, part of which is still in existence. The steps are 45 feet wide, while each step is 2½ feet from front to back and 5 inches in depth. For the sake of comparison it may be noted that the most famous steps in Rome were not more than 17 feet wide.

But it is to the astonishingly complete system of drainage with which the palace was provided that we would call attention here. The sanitary equipment included lavatories, bathrooms, sinks, and drains complete with manholes for inspection ; the whole system, as Mr. Ronald Burrows puts it in his book *The Discoveries in Crete*, being " staggeringly modern." A main conduit of stone, one metre by one-half, and lined with smooth cement, received drainage from the upper floors by a number of stone shafts. Through these shafts the surface water from the roofs of the palace buildings was led, so as to ensure a periodical flushing of the drains. Connected with this system were the lavatories and other sanitary conveniences.

Some of the terra-cotta pipes which served as connections to the main drain are still preserved. The main drain itself was over 3 feet high and 2 feet broad, so that a man could easily get along it. The pipes are round in section, 6 inches diameter at one end and rather less than 4 inches at the other. The length of each pipe is about 2½ feet. They were joined together by placing the small end of one pipe in the large end of another, jamming at the joints being prevented by a stop-ridge which ran round the outside of the narrow ends a few inches from the mouth. When in place the pipes were cemented together.

By the side of one of the staircases a stone runnel is provided for carrying off the surface water, and great ingenuity is shown in the method adopted to prevent the water from descending too rapidly, and so splashing over, owing to the steepness of the gradient. The runnel is so formed that the water was compelled to follow a series of parabolic curves, thereby checking the flow.

Equally notable developments, believed to date back to about 3000 B.C., have recently been discovered at Mohenjo-daro, in western India. Here whole streets of roomy and well-built houses have been excavated, each furnished with its own wells and bathrooms and provided with covered drains connecting with main drains in the streets. " Every street and alley-way," says Sir John Marshall, Director-General of Archæology in India, " seems to have had its own covered conduits of finely-chiselled brick, laid with a precision which could hardly be improved upon." Careful jointing of the brickwork was essential, it may be added, owing to the absence of limestone and other cementing materials in the neighbourhood of Mohenjo-daro.

We shall have occasion to refer again to this subject when discussing developments in ancient Rome. Meanwhile we propose to direct the reader's attention to another highly important aspect of early engineering progress—the beginnings of transport.

CHAPTER V

THE DAWN OF TRANSPORT

I

First Essays in Flotation

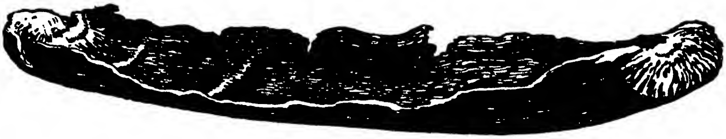
When we consider the world in which our prehistoric ancestors lived, it is easy to understand why the earliest civilisations developed in regions dominated by great rivers. Means of internal communication constitute one of the first essentials of a civilised community. Locomotion by land was limited by natural barriers, such as forests, jungles, swamps, and mountain ranges. Rivers, on the other hand, afforded not only ample supplies of water for drinking and irrigation, but also a ready means of transport and travel.

Not that there would be any great inducement to travel in those days. The stranger in a strange land would be likely to meet with little but hostility from those he encountered on the way. Death lurked about every bend in the river. There was little security beyond the familiar territory occupied by one's own tribe.

Yet there were undoubtedly adventurous travellers, both by land and by river and sea, even in the earliest stages of civilisation. Some men have in all ages been born wanderers, driven by curiosity and the spirit of adventure. Others have been impelled to travel by famine, pestilence, warfare, superstition, trade, and, in later times, by the desire to consolidate kingdoms and empires. But whatever the inducement, rivers must for long have provided the readiest means of moving from one place to another.

After having used a floating log of wood for transport purposes, and found it inadequate, it would be very natural to pass on to the construction of rafts by binding a number of logs together. This would be accompanied by the hollowing out of trees by burning and the use of primitive tools. Other vessels, such as canoes and coracles, would be constructed by lacing rushes, flags, or reeds together. Bark, and basketry caulked with clay or bitumen, presented alternative possibilities. Coracles are still used in various parts of the world, constructed on lines similar to those used perhaps 8,000 years ago. Some vessels were probably made out of skins, similar to those still in use among the Eskimos. The buoyancy of rafts was increased by attaching inflated skins to them, a practice common to peoples as widely separated as those of Mesopotamia and Peru.

Herodotus gives some interesting particulars of the coracles in use on the Euphrates in his time. They must have been of a considerable size, since he remarks that every vessel had a live ass on board, sometimes more than one, in addition to the cargo and two men. The vessels were only used for one-way traffic. First of all the men would cut the ribs out of willows that grew in Armenia. The next step was to put the ribs together and cover them with hides, " neither making any distinction in the stern nor contracting the prow, but making them circular like a buckler. Then, having lined this vessel throughout with reeds, they suffer it to be carried down by the river freighted with merchandise, but they chiefly take down palm casks full of wine." [1] After arriving at Babylon and disposing of the freight, they sold the framework of the boat, piled the skins on the asses, and returned by land to Armenia. Owing to the rapidity of the current, it was quite impossible to propel the vessels upstream.



A prehistoric dug-out canoe (*British Museum*).

The step from constructing such primitive vessels to an equally primitive boat building would be a very short one, and had probably been taken some thousands of years before the time of Herodotus. In what part of the world men first began to build boats we do not know. It is certain, however, that the Egyptians were among the first to progress beyond a primitive stage in the art of navigation.

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[1] Herod. I, 194.

2

The Transition to Boats and Sailing Ships

From paintings on early Egyptian pottery we learn that boats were familiar objects on the Nile in prehistoric times. Sailing ships were rare but not unknown. The usual mode of propulsion was the paddle or oar, and steering was effected by a large rudder. Both the Nile and the Mediterranean Sea provided special facilities for this form of transport. For a considerable portion of the year the river is almost as easy to navigate up-stream as down, particularly with the use of sails ; and sails had come into common use in early Dynastic times. Herodotus states that, when necessary, towing from the shore was adopted to assist boats going up the river. On the Mediterranean, owing to the fact that the wind may drop for days together, the use of oars persisted long after sailing had become a fine art, and in fact large boats of this type have been used on the Mediterranean Sea right down to modern times.

Large ships were already navigating the Nile in the First and Second Dynasties, and were traversing the Mediterranean in the Third Dynasty. Under the Sixth Dynasty we know that vessels sailed as far as Somaliland. And when we come down to the days of the Middle Kingdom (about 2300–1500 B.C.) we find sea-going had become so customary that mariners' yarns were already in existence and recorded in the literature of the times. One of these, the *Story of the Shipwrecked Mariner*,[1] typical of such tales in all ages, relates how a sailor set out from a harbour on the Red Sea for the mines of the Sinaitic peninsula, in a large ship 60 metres in length and 20 metres in breadth and carrying 120 men. The story of how the ship was wrecked ; how all his companions perished, and he was cast on an island by a wave ; of how he carried on a lengthy conversation with a gilded and bearded sea-serpent 15 metres long, and after other adventures returned to Egypt, reads like one of the exploits of Baron Munchausen, or an adventure of Sindbad the Sailor.

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[1] From a papyrus now in Leningrad.

The sea-going ships of the Egyptians were very similar in build to those plying on the Nile.

> " The hull, which was built on a curved keel, was narrow, had a sharp stem and stern, was decked from end to end, low forward and much raised aft, and had a long deck cabin ; the steering apparatus consisted of one or two large stout oars, each supported on a forked post and managed by a steersman. It had one mast, sometimes composed of a single tree, sometimes formed of a group of smaller masts planted at a slight distance from each other, but united at the top by strong ligatures and strengthened at intervals by crosspieces which made it look like a ladder ; its single sail was bent sometimes to one yard, sometimes two, while its complement consisted of some fifty men, oarsmen, sailors, pilots, and passengers. Such were the vessels for cruising and pleasure. The merchant ships resembled them but they were of heavier build, of greater tonnage and had a high freeboard. They had no hold, the merchandise had to remain piled up on deck, leaving only just enough room for the working of the vessel." [1]

The keel was commonly strengthened by a rope truss running fore and aft.

Egyptian ships appear to have been propelled first by paddling, then by rowing ; the men at the oars usually facing the stern of the vessel. The oars are depicted as being so close together that probably there were two lines of rowers on a side. Although in course of time boats were built with several banks of oars, it remained for Grecian naval architects to develop such possibilities to the utmost, introducing large vessels with as many as thirty banks of oars. These " banks " were probably not tiers, but groups which worked together. But even so, the crew on occasion consisted of several hundred men.

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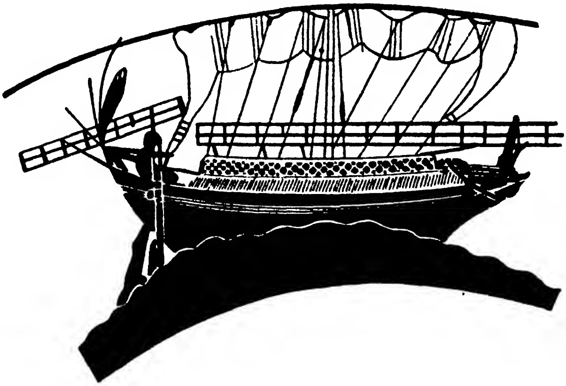
[1] Maspero, *The Dawn of Civilisation.*

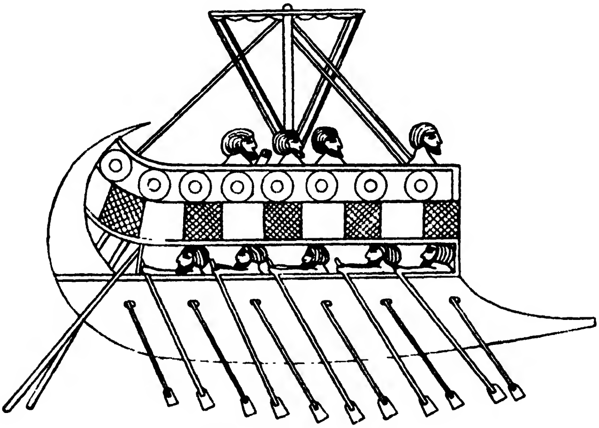
The vessels used by that great trading people the Phœnicians followed similar lines to those of the Egyptians but were larger, and probably more seaworthy. For them, as for the Minoans of Crete, navigating the Mediterranean was an everyday affair. They sailed from port to port and from island to island. The ancient legends and fables of Greece are much concerned with sea-going adventures, no doubt based on their own experiences and on those of the Minoans and Phœnicians. The latter people made long journeys to Spain. Hanno, for example, appears to have passed Cape Verde ; and as he is believed to have captured gorillas he probably reached Liberia or Sierra Leone. The description by St. Paul of his adventures on a cargo-vessel sailing from Myra to Italy gives an excellent idea of the hazards run by these ancient mariners.



Greek merchant ship, 6th century B.C.

About 600 B.C. some Phœnician sailors, commissioned by Necho, of the XXVI. dynasty of Egypt, actually circumnavigated the entire continent of Africa, returning in the third year from their departure down the Gulf of Suez to their point of departure by way of the Mediterranean Sea.

Both the Egyptians and Babylonians constructed canals to facilitate shipping. Senusert III. made a canal past the first cataract at Asswan, 34 feet wide and 24 feet deep, large enough for any Nile cargo boat, and, says Flinders Petrie, " much better for traffic than the present railway." There is reason to believe that a canal may have joined the Nile and the Gulf of Suez as early as 1950 B.C., making it possible for ships to pass to and fro between the Mediterranean and the Red Sea some 3,800 years before the Suez Canal was constructed. It should be stated, however, that there is some difference of opinion about the date when the Nile-Suez Canal was really made. Strabo says it was first cut by Rameses II., that is, not until after 1292 B.C. Herodotus puts the date later still, stating that the canal was begun by Necho (about 600 B.C.) and completed by Darius. Similar enterprises were undertaken by the Babylonians to enable shipping to reach inland ports with greater facility.



A Phœnician galley.

Harbour construction was a parallel development. There are the remains of a great harbour, of unknown date and now submerged, at Alexandria ; whilst harbours on a smaller scale were constructed by the Phœnicians at Tyre, Sidon, and Utica. Phœnician civil engineers also constructed docks and erected warehouses at Cadiz to facilitate their shipping and trading relations with western Europe and probably with the British Isles.

3

Roads before the Romans [1]

Despite a widespread belief to the contrary, the Romans were not the first to develop long distance roads. The Hittites anticipated them in this regard by many centuries. The Romans, it is true, made roads such as the world had never seen before, but it was not so much new knowledge they brought to this work as vision and determination.

The development by the Hittites of a road system which eventually linked up Asia Minor with Babylonia, Elam, and probably with Syria and Egypt as well, was no doubt largely due to the international trading activities of this people, who dominated Asia Minor for some hundreds of years and developed a civilisation which was able to challenge on equal terms the might of Egypt and other neighbouring empires. Hittite business documents, dating from about 2000 B.C., or even earlier, and discovered at Cæsarea Mazaca in the heart of Asia Minor, attest to extensive trading relations and routes between this people and other nations. It is still possible to trace with considerable confidence the main routes which served these international traders of several thousand years ago.

The earliest of such ancient highways of which we have any knowledge ran east and west through the heart of Asia Minor, and down through the uplands beyond the Euphrates and Tigris rivers, terminating at last at Susa, about 250 miles almost due east of the ancient city of Babylon. When the Persians overran Mesopotamia and Asia Minor in the 6th century B.C., they called this highway "The Royal Road," but as we shall see later, the name was already applied to at least a portion of it before that time.

The road followed a route which had probably already been in existence for hundreds, and it may be for thousands, of years. Linking east and west it brought alien peoples in contact with one another, serving as a great medium for trade, communications, and war. It saw kingdoms wax and wane. Principalities and powers grew to the zenith of their glory and passed away. Empires clashed and their boundaries swayed to and fro with the fortunes of war, but still the ancient route remained.

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[1] Among the most important of human necessities are water and salt. It is probable that the natural location of these had much to do with determining the great overland trade routes of antiquity (*e.g.*, see Herodotus, IV, 181 ff.).

The general trend of the road is still to-day indicated over portions of its length by Hittite monuments in its vicinity. Guided by the evidence thus afforded, and particulars derived from Herodotus and other sources, we may say with some degree of assurance that the road ran from Sardis eastward, passing south of Gordium where Alexander " untied " the knot, through what is now the city of Angora, across the river Halys to the ancient capital of the Hittite kings, Bogaz Keui, then south-east to Cæsarea Mazaca, and across the great Anti-Taurus range to Melitene, or possibly Marash. After this the road crossed the Euphrates at Samosata, which, according to Strabo, was the starting point of the great overland route to India. From here the Royal Road ran south-east to Harran, the caravanseri city to which came Terah with Abraham from Ur, as related in Genesis. Then passing on again, we come to Nisibis, where in a later age Tigranes had his treasure houses, and so to Nineveh, the capital of Assyria. Here Sennacherib, king of Assyria from 705-681 B.C., left two records on which he tells us how he extended the main street of Nineveh along the track of the Royal Road. On a memorial stone he placed this order : " Royal Road. Let no man decrease it."[1] The breadth he gave as 78 feet. From Nineveh the road continued through Arbela and the western uplands of Elam to Susa.

There is evidence to show that a number of branch routes radiated from the main highway. It has been suggested that one such route, reaching from Sinope on the Black Sea to the Mediterranean *via* the Cilician Gates, was older even than the Royal Road itself. This, if correct, would account for the curiously zigzag course of the Royal Road : the section of road between Bogaz Keui and Mazaca serving for traffic going north and south as well as for that passing east and west.

Where such ancient roads passed through cities we know that they were sometimes paved in Babylonian and Assyrian times. We have already noted in a previous chapter that the Street of the Procession in Babylon was paved with slabs of limestone 3 feet 6 inches square. Stones marking distances were sometimes used. Of the condition of the roads beyond the vicinity of the towns we know little, though we know that wheeled traffic passed over them in addition to animal caravans which were the usual means of trade transport. Though there is no direct evidence that the Royal Road was in any sense an " engineered " road, yet we may hazard a guess that it was more than a mere track, since it continued in use long after the centre of power had passed from Bogaz Keui and the route followed had therefore become circuitous and unsuitable.

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[1] Olmsted, *History of Assyria*.

A note may be added on roads which existed in other lands at this time. The people of Crete made one road which was paved over a considerable distance with slabs of stone to a width of about 4½ feet. Beyond the paving, the road was on either side made with rubble well rammed down. There were several other engineered roads in Crete, also in the neighbourhood of Mycene, with ramps and even culverts. We have already mentioned the road of polished stone in Egypt, said to have been used for transporting materials from the Nile to the Great Pyramid. This was one of a number of similarly graded roads of solid construction, each of the other pyramids having its specially prepared road. Though these were processional avenues eventually, it is not unreasonable to suggest that originally they may have been engineer-made tracks designed for heavy transport purposes. Sir Flinders Petrie remarks that " where an ordinary road crossed the desert, all stones were swept to the sides, leaving a clear space 85 feet wide ; sometimes waymarks were put at each one-third of a mile and four miles." It may be added that this method of " road-making " has persisted in oriental countries until modern times—hence the almost total destruction of paved Roman roads by Turks and Arabs.

For Assyrian records of engineered roads in Armenia and other highland countries the reader may be referred to Olmsted's *History of Assyria.* It is not our intention to discuss this matter in greater detail here ; our purpose being merely to indicate that the need for roads was already widely felt, and rudimentary attempts to meet that need were already being made, long before Roman engineers raised road-making to a level of perfection which has only been excelled in the times in which we now live.

4

The First Wheels and Wheeled Vehicles

There is some evidence that several important devices involving rotary motion, including the wheel and axle, were originally invented in western Asia. The potter's wheel, for example, was known in Asia for centuries before the Egyptians made use of it. We are aware that some authorities do not agree with this statement, but the general trend of opinion is against them. The lathe was used in Syria at a time when the Egyptians were importing its products and engaged in the laborious task of imitating them by hand. There is nothing to indicate that the rotary cylinder seal, and the rotatory spindle-whorl, were used earlier in Egypt than in Asia. The earliest-known representation of a pulley comes from Assyria. Finally, the wheel and axle for transport, as already indicated, was unknown in Egypt until Asiatic conquerors brought the wheeled chariot and horse to that country.[1]

There can be little doubt that the first vehicles were sledges. In one of the oldest documents in the Sumerian writing so far discovered, there appears a representation of a sledge. And for long after the invention of the wheel and axle, sledges provided the only possible means of transporting very heavy objects on land ; being adopted for this purpose both in Egypt and Mesopotamia. It is interesting to note in this connection that when the Assyrians used sledges they also made use of wooden rollers, whereas the Egyptians appear to have relied solely upon lubricants poured under the runners to reduce the effort required.

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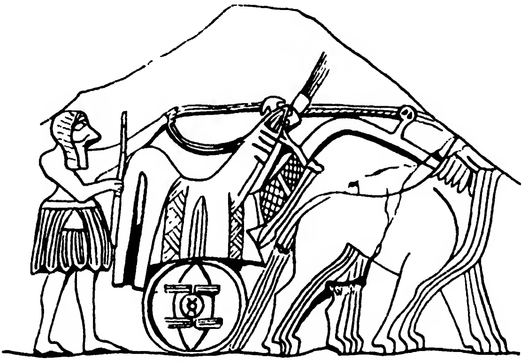
[1] But note that the rotary drill was used in Egypt from very early times. It seems safe to assume that the earliest application of rotary motion to the requirements of man was in the operations of boring and drilling. The accidental production of sparks would lead to the invention of the fire-drill.

Whether the Sumerians invented the wheel and axle we do not know. We do know, however, that already by 3000 B.C. they were using chariots and four-wheeled wagons, the wheels being sometimes equipped with leather tyres.[1]

The earliest type of wagon, resting on an axle rigidly connected with a pair of wheels, probably developed from the use of several logs as rollers. Cutting the logs away in the middle would result in a rigid combination of wheels and axle. One or two of these combinations fixed to the wooden frame but free to rotate would complete the transition from sledge to wagon. The wheel rotating on the axle would come later, and the spoked wheel later still. A pair of oxen or other animals yoked in front supplied the motive power. To the yoke was fastened the pole projecting from the wooden frame.



Earliest known illustration of a wheeled vehicle that can be approximately dated. From a Sumerian stone plaque, *c.* 3500–3000 B.C.

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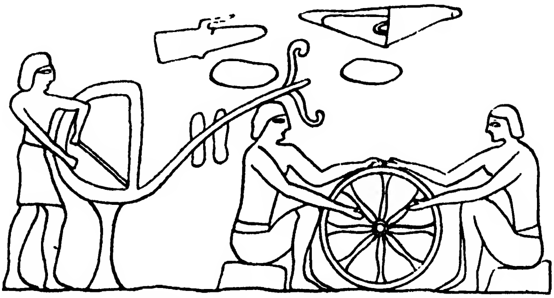
[1] See *Antiquity*, March, 1928.

Origins of the Wheel.—The really puzzling invention is the loose wheel revolving on a spindle axle. It has its counterpart in the perforated cylinder-seal, and I am inclined to suspect that the use of a decayed or soft-hearted roller led to the insertion first of terminal trunnions; then the trunnions jammed in their bearings and worked free of the roller, becoming pivots like the centres of a lathe. Only after that did someone put the pivots outside the frame instead of inside, bisect the roller, and invent the linchpin. But *why*?—J. L. M.

The knot fastening the pole to the yoke was an ingenious but simple contrivance. It no doubt seemed marvellous to the ignorant rustic, just as its various adaptations on board ship frequently puzzle the landsman to-day. This simple form of wagon is still to be seen in the fields of Asia Minor. It can be constructed by any peasant out of wood ready to his hand, an advantage where carpenters are scarce and unskilful.[1]

The Egyptian chariot was at first a copy of those imported from other countries, although in course of time a lighter vehicle appears to have been evolved, suitable for rapid travelling over the desert. From an engineering point of view, however, the Egyptians, like other peoples, were backward in grasping the principles of efficiency in construction ; the weight of body and passengers being too much in front of the axle, and so throwing an unnecessary strain on the horses. Ancient harness was also unpractical, the load coming on the chest of the horse. The wheels were of very broad gauge, and covered (like the earlier examples from Ur) with leather tyres. Leather was also used for the sides of the body, laid over wood, which was used in its construction. As the native Egyptian woods were not suitable for chariot manufacture, having neither the toughness nor the strength desired, foreign woods were imported such as beech ; while birch and cherry bark were used for decorative purposes.



Egyptian chariot manufacture. After Maspero.

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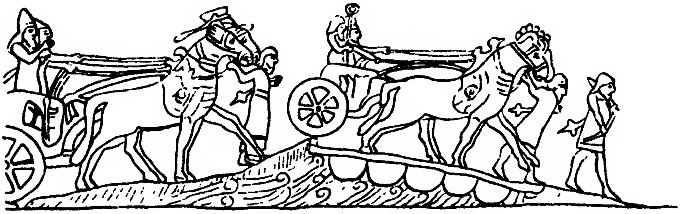
[1] Ramsay, *Asian Elements in Greek Civilisation.* See also *Antiquity*, June, 1931.

The only other early use of the wheel for transport of which there is any record is in connection with the battering ram. The nature of this example of ancient military engineering, and the method of its application, can be gathered from illustrations depicting battering rams as used in Assyria in the time of Assurnasipal (9th century B.C.). The ram was operated from the shelter of a movable tower, the tower and the battering ram thus forming together a very potent factor in both offensive and defensive operations. We may perhaps see in this development the origin of the armoured car and the " tank " of the present day.



Assyrian chariots crossing a bridge of boats, 859–824 B.C.

CHAPTER VI

THE TRANSITION TO IRON

I

The Dawn of the Iron Age

Few developments can have been fraught with consequences more momentous in their effects upon the course of man's material progress than the discovery of iron. And few have been the subject of so much speculation and dispute.

The most diverse and contradictory theories about this discovery have been propounded by metallurgical, archæological, and scientific experts. According to some authorities the earliest iron known to man must have been of meteoric origin. In support of this theory we are reminded that the Egyptians called iron " the celestial metal " and the Babylonians referred to it as " the stone of heaven," while the Hittites used the mark for divinity in their ideogram representing iron. That iron known to date back to very remote times has been found only in limited quantities is also said to support this view. On the other hand, Sir Robert Hadfield has expressed the opinion that " the use of iron, including in this term the combination of iron and carbon known as steel such as is produced by the fusion or cementation processes, has without doubt existed from a time dating back to a very early period." He also holds the view that the people of ancient Egypt must have had steel tools in order to work in granite and other hard materials, but " owing to the avidity of the oxygen present in the air for this metal, it has been most difficult to obtain ancient specimens." President Hoover, in his translation of Agricola's *De Re Metallica*, has a footnote to the same effect. But Professor Flinders Petrie tells us that the Egyptians worked granite with jewelled drills and saws and the use of emery. And Maspero, as we have seen, records how soft iron tools suffice for working the hardest stone.

Other authorities have suggested that the use of iron in Egypt was delayed owing to the metal being associated with Set, god of the waste and the desert, a personage representative of physical evil and therefore an object of fear. According to yet another theory, the innate conservatism of the human mind caused men who were used to the more familiar and attractive looking metals, and highly skilled in their manipulation, to resist what may have for long seemed an undesirable innovation. Finally, we may note the extreme view (recorded by Dr. John Percy, F.R.S., Mr. St. John V. Day and others) that the use of iron actually preceded the Age of Bronze !

Let us examine the available evidence.

The earliest known Egyptian specimens of worked iron are some small beads found in a tomb of the pre-dynastic period. They were almost certainly made before 3500 B.C., and possibly as early as 5000-6000 B.C. Next we come to a piece of iron found in the Great Pyramid. This, if authentic, would date back to about 3000 B.C. In view of the fact that doubt has been cast on the ancient origin of this particular example, we may quote the written testimony of the finder :

> " This is to certify that the piece of iron found by me near the mouth of the air-passage in the southern side of the Great Pyramid at Gizeh on Friday, May 26th, was taken out by me from an inner joint after having removed by blasting the two outer tiers of the stones of the present surface of the Pyramid, and that no joint or opening of any sort was connected with the above-mentioned joint by which the iron could have been placed in it after the original building of the Pyramid. I also showed the exact spot to Mr. Perring on Saturday, June 24th. (Signed) J. R. Hill, Cairo, June 25th, 1837."

To the foregoing circumstantial deposition is added the testimony of three other men. The combined declarations are certainly of a nature to carry conviction.

Later, there are several pieces of a pickaxe believed to be of the Fifth Dynasty, and specimens of iron found in association with objects of the Sixth and Twelfth Dynasties. With the passing of the centuries Egyptian examples multiply until in the Nineteenth Dynasty (*c.* 1320-1200 B.C.) we find that iron is better known though still far from plentiful. We know that during this period iron was being imported, which certainly appears to support the statement that the Egyptians did not work their native ores in those days. Rameses II., who lived about 1250 B.C., wrote a letter to Hattushil, the Hittite king, in which he asked that a supply of smelted iron might be sent to him. The reply of Hattushil, which has also been found, was to the effect that none was available in his stores at the moment. This reply may quite possibly have been a " terminological inexactitude " ; the northern potentate not wishing to equip a potential foe with a material which was at that time beginning to prove its superiority to bronze in warfare.

Whether or not the Egyptians were late in working their native hæmatite, we know that for long after the times we are considering, they clung tenaciously to the use of copper and bronze for many purposes. To such a remarkably high level did Egyptian bronze founders carry their art that some of their castings in this alloy were no more than $\frac{1}{50}$th of an inch thick. When at length iron supplanted bronze for weapons and tools in Egypt, it came too late to restore to its former supremacy a civilisation which was by then already decadent.[1]

In Mesopotamia fragments of iron used for ornamental purposes appear in graves at Ur which have been dated at 3500-3000 B.C. That iron was not generally used in Mesopotamia until a much later date, probably not before 1000 B.C., is perhaps indicated by the existence of bronze weapons, one bearing the name of an Assyrian king, Adadnirari I. (*c.* 1330-1295 B.C.), and others found at Nimrud, a city believed to have been founded about 1300 B.C. An inscription of Tiglath-Pileser I. (*c.* 1100 B.C.) mentions an iron hunting spear, and Tiglath-Pileser III. (745-722 B.C.) refers to iron as part of the royal spoils from Commagene, north of Syria. Among other specimens of iron found in Mesopotamia *may be mentioned* a number of iron mace-heads, knives, hooks, grappling irons, chain cables, picks, mattocks, hammers, ploughshares, and the tongues of bronze bells ; but none of these can be held to modify the view that iron did not come into general use in this region much before 1000 B.C.

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[1] In an interesting paper by Sir Harold Carpenter and Dr. J. M. Robertson, read before the Iron and Steel Institute, May 1st, 1930, and entitled *The Metallography of Some Ancient Egyptian Implements*, the authors give evidence to show that carburising, quenching, and the advantages of heat treatment generally, were known and appreciated in Egypt centuries before the Christian era.

There is reason to believe that the peoples of Syria also began to use iron freely at this time. Though a few centuries earlier the Philistines were using bronze weapons, yet at the time of their struggle with David, which was probably about the 10th century B.C., their offensive armament is stated to have been of iron.

The Hittites of Asia Minor used iron at an earlier date, as we have seen. About 1250 B.C. there appear to have been stores of this metal in Commagene and Kissu-Wadna, both of which were within easy reach of the Royal Road. We have already remarked that from Cæsarea Mazaca a branch road probably ran north to Sinope ; while another may have linked up with Trebizond on the southern shores of the Black Sea. Both these roads would pass through the land of the Chalybes ; a people who, living in dens and caves of the earth, were long reputed to be pioneers in the art of smelting iron.

One of the earliest sites of ironworks in Europe is near Hallstatt, in Austria, within fairly easy reach of the Danube.[1] Here again 1000 B.C. may be mentioned as an approximate date for the establishment of the industry in this region. These ironworkers, belonging to what is known as the Hallstatt period, may possibly have discovered the art of smelting iron independently of the Chalybes, though this is not probable. Communication between the two centres was a relatively simple matter.

The Ægean civilisation centring about Crete was destroyed before its people knew of iron for other than ornamental purposes. Indeed, it is not improbable that the overwhelming of this people, by strangers believed to have come from the region of the Danube, was rendered possible by the invaders being armed with weapons made of the tougher metal.

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[1] For an authoritative discussion of this matter, see Chapter VII. of *Who were the Greeks ?* by John L. Myres. It appears that there were land routes facilitating communication with Hallstatt from the Danube.

Italy learned of iron from the Etruscans, who probably brought the knowledge with them from their old home in Asia Minor. Iron was just coming into use in Europe about the time they began to settle on the western coasts of Italy, and here the Etruscans found plentiful supplies, the ores being particularly abundant in the neighbouring island of Elba. From the 8th century B.C. onwards, iron came into common use all over Etruria. The newcomers used this metal to a prodigious extent, and their knowledge of smelting and forging must have been obtained elsewhere before their arrival. The theory that they came from Asia Minor is certainly supported in this respect.

Passing westward, the dawn of the Iron Age must be put at a more recent date. It is doubtful whether iron came into use even in limited quantities in Britain before about 500 B.C.

Iron in India and the Far East

Turning to the East, we find in India a land where there is no native tin, and therefore working in bronze must have been dependent on imports. Iron ores and timber, on the other hand, are plentiful. In purity of ore the iron deposits of India are said to rank among the finest in the world. They are found in many parts of the country, and appear to have been worked from a remote antiquity. The metal is mentioned in the ancient Vedic literature, which on the basis of astronomical references is said to date from about 1400 B.C. The Hindus, however, believe that the *Rig-Veda* was in existence by at least 3000 B.C. This, like the traditions of other races, has been doubted ; but in these days when many statements in the Bible, and in the works of writers like Homer and Herodotus, once considered doubtful, have been confirmed by the work of archæologists, we may well hesitate to reject the testimony of the ancient Indian records.

It is just possible, therefore, though perhaps hardly probable, that the smelting of iron was known in India even earlier than in Asia Minor and Europe. Perhaps it is not without significance that Strabo's " road to India " started from Samosata ; that is, from near the site where an iron emporium existed in the second millennium B.C. That there was some link, direct or indirect, between the two lands at that early period we know from the fact that records have been discovered at Bogaz Keui, in Asia Minor, belonging to the 14th century B.C., containing the names of the Indian deities Mitra, Varuna, and Indra, and the heavenly twins, the Nasatyas. Through the work of archæologists we are now beginning to learn something of ancient cities in the north of India which—as we have seen—were almost modern in their architecture, planning, and sanitation. In the west of this northern region, objects have been found which bear a striking resemblance to similar Sumerian objects of 3000 B.C., pointing to traffic across Persia at a period considerably more remote even than that we are considering here. It must be added that there is no evidence of iron having been known at such an early time. But the very fact that the discovery of iron was preceded by facilities for long distance intercommunication makes it very difficult to say, with any assurance, that knowledge of this metal, when it did come, spread from west to east or *vice versa.*

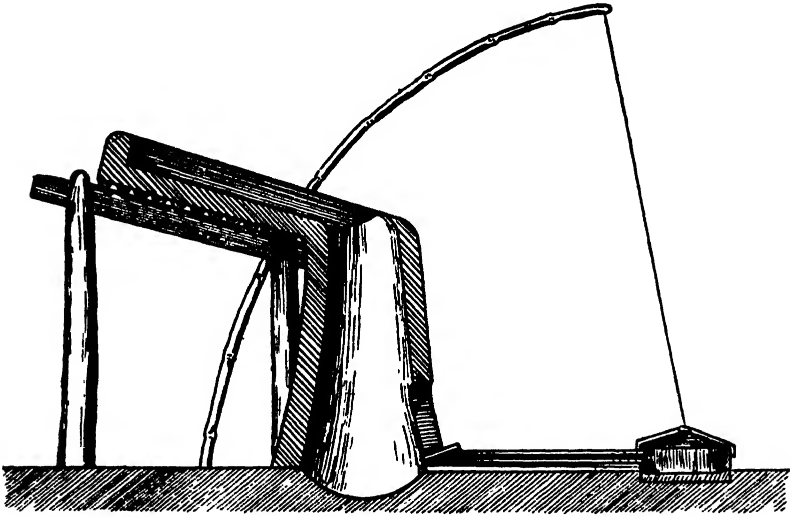
With some exceptions, it may be said that where there are hills in India there iron is to-day found and worked. Local tradition, such as it is, puts the origin of the industry back to " the dawn of history." Later, iron appears to have been widely used, particularly for warlike purposes. The very large and ancient forged iron columns and beams found in India cannot be satisfactorily dated. Although they no doubt belong to a much later period than that we are now considering, possibly as late as 300 A.D., we may mention here that one, found at Delhi, weighs about 6 tons and is over 22 feet in length. Another, at Dhar in Central India, now broken, was 43 feet long and must have weighed about 7 tons.

We have no definite knowledge of iron in China before about 700 B.C., but as shortly after that date the industry had become important enough to supply revenue by taxation, the metal had no doubt first come into use some centuries earlier than this. The tax stimulated succeeding governments to promote production as well as consumption. Three hundred years later iron began to be used in China for the manufacture of weapons, and later still the products of Chinese ironworks became so widely known that they even reached Italy ; being, according to Pliny, the best of all the various kinds of iron coming to Rome.

Primitive Methods of Iron Smelting

We cannot say definitely what methods were adopted by the early pioneers in iron smelting, but it seems reasonable to assume that primitive methods still in use among backward races have persisted from a remote past practically unchanged. Among the present day natives of Inner Africa—a region where iron is very easy to obtain, the very rivers being coloured brown and red by hæmatite and bog-iron ores—the smelting furnace is simply a shallow pit with lateral holes to admit air. In some cases a circular rim of clay is provided, and in others a blast-furnace is constructed by raising the walls of the pit to a height of about 6 feet. In this layers of wood and ore are piled in succession, the fire is lit, and allowed to burn out. The ore is brought to a red heat, when the oxygen of the ore combines with the carbonic oxide produced from the partial oxidation of the fuel, forming carbonic acid gas and metallic iron. The gas passes to the atmosphere and the metal escapes through the holes provided at the base, or more generally is removed while still spongy.

The natives of India follow a similar procedure, constructing a small furnace of clay, into the bottom of which two nozzles are introduced, connected with a bellows by bamboo tubes. The bellows consist of two wooden bowls each covered with a skin like the end of a drum. This skin is depressed by the operator placing his foot upon it, while at the same time he covers a small hole in it with his heel. The skin is raised again by the pull of a bent bamboo rod attached to it by means of a cord. By stepping on first one and then the other skin a fairly continuous blast is kept up. Bellows of a similar type, the skin being pulled up by hand, were in use in Egypt in the 15th century B.C., and the same principle is also seen in the bellows used to-day by native smiths of Central Africa ; the skins in this case being raised and depressed by rods held in the hand. By means of such bellows the iron after smelting is brought to a glow in the fire and then worked up on a stone anvil to the requisite shape.



Primitive Hindu smelting furnace and bellows.

The iron after reduction contains earthy matter. Silica is frequently present in the latter, and protoxide of iron will form a fluid compound with silica at a comparatively low temperature. Some of the protoxide combines with the earthy matter, and slag is formed. A mass of malleable iron in pasty form is obtained, the slag is squeezed out by pressure while the mass is still red-hot, and the metal is obtained in a form which can be subsequently worked into shape.

Among the Burmese a furnace is used which consists of a hole dug in a bank to a depth of about 10 feet and some 2 or

3 feet from the edge. A rectangular opening is made through the lower part of the bank, about 1 foot high and the full breadth of the furnace. Through this opening the metal and slag are eventually removed. During the smelting process the opening at the base is closed with clay, through which pass a number of small tubes or primitive tuyères. In Central India continuous working is effected by removing the iron through the top of the furnace, the slag being run out at the base. The furnace can then be re-charged again while still hot.

What is known as the "Catalan" furnace, still used in quite recent times in the Pyrenees and elsewhere, is clearly based on similar methods; though showing some slight improvement in the size of the furnace and the method of obtaining an air blast. It consists in general of a silicious stone bottom covered with charcoal powder. The front part of the furnace is filled with ore for reducing, while charcoal is placed at the back. The whole is coated over with a layer of fine ore mixed with charcoal dust to check the combustion, and further layers are added from time to time during the whole process. The blast is applied through a tuyère at the back, gently at first and later with greater intensity, the whole contents of the hearth being stirred and the reduced metal becoming agglomerated. By prolonging the period of reduction the carburisation of the metal is ensured while a more rapid blast impinging directly on the mass of iron and slag results in a softer and less carburised product.

Some forges of this type have been constructed to hold 3-10 cwts. of ore. In others the principle of warming the blast by means of the waste heat from the furnace has been adopted, resulting in an appreciable reduction in the quantity of charcoal required.

To produce steel by such primitive means, everything possible must be done to ensure maximum carburisation. The slag is removed more frequently and the ore is exposed for a longer time to the reducing and carburising gases. It is also found that the presence of manganese is very helpful, probably owing to its ability to replace iron in the slag. A slag in which some of the iron is replaced by an equivalent quantity of manganese is more liquid and apparently has not the same tendency to cause decarburisation at the temperature at which this process is carried out. Oxidisation of the iron by the blast entering through the tuyère also must be avoided as far as possible, as the presence of oxide of iron makes it more difficult to obtain steel. The Hindus probably produced steel known as *wootz* before the dawn of recorded history, by regulating the conditions in the furnace, maintaining a high temperature, and ensuring the requisite degree of carburisation. In this process the iron is enclosed in unbaked clay crucibles together with some chopped wood and leaves before being placed in the furnace.

From apparatus of this primitive type the large scale and highly efficient furnaces used in modern iron and steel works have been evolved in quite recent times.

CHAPTER VII

COUNTING, MEASURING, AND TIME RECKONING

I

Rules of Thumb and Fingers

MAN must have been driven to a consideration of numbers at a very early stage in his career. And because the most commonly used language-forms and counting-symbols have a way of persisting age after age, we find, even in present day systems of enumeration and measurement, many traces of their humble beginnings in the days when man almost universally counted on his fingers in fives and tens—sometimes getting up to twenty by the aid of his toes.

Rules of thumb and fingers, and measures taken from the human body generally, survive in many forms. The Roman numerals, I . . . V ; VI . . . X ; XI . . . XV ; and so on, are clearly descended from five-finger counting. Ability to count up to five, once no doubt quite an accomplishment, accounts for such sayings as the English : " He knows how many beans make five," the German : " He can scarce count five," and the Spanish : " I will tell you how many make five." And there are races in Africa and elsewhere still using terms such as " hand " for five, " hands " or " half-a-man " for ten, " two-on-the-foot " for twelve, and " man " for twenty.

Among primitive people there is usually great vagueness about larger numbers. Sometimes we even find savages who say " heap " or " plenty " for any number beyond five. The word " heap " was also used by the ancient Egyptians to indicate an unknown quantity. Some savages of the present day have difficulty in getting beyond two. The Bakairi Indians of Brazil, for example, have only two articulate numerical words. The native Queenslanders say *burla* for two, and *burla burla* for four. Thus, as Allen Upward pointed out, the example of absolute truth given by Descartes, namely, that " twice two is four," turns out on examination to be little more than repetition. " *Burla Burla* is *Burla Burla.*"

In ancient Egyptian hieroglyphics an object such as a man was often marked with a single line if one man was indicated, two lines if two, but three lines might mean three or many. This seems to be a survival from the time when anything more than two was indefinite.[1] The use of fingers, pebbles, beans, and shells has in all ages proved to possess considerable advantages over words for readiness in apprehension of larger numbers. In a previous chapter reference was made to the painted pebbles of the Azilians as possibly being associated with very early attempts at enumeration.

Units of linear measurement were obviously associated with body and kindred dimensions from the first. Evidence of this is still to be found in words such as " foot," " pace," " ell," (an arm's length, from *ulna*), and the French *pouce* for both thumb and inch. " Rod " and " pole " doubtlessly originated from the stick or spear which was as familiar to early man as the parts of his own body. It is not surprising, therefore, when we turn to the earliest known measures, to find that the peoples of antiquity based their calculations on similar units.

Among primitive aids to counting other than body measurements are notched sticks and knotted strings. From these to some elementary form of abacus is no great step to take, and we find in fact that this instrument has been used at one time or another by nations in nearly every part of the world. The form which it usually takes is that of a rectangular wooden frame strung with wires on which beads have been threaded. A more primitive type consisted of a board covered with sand. Grooves were made in the sand with the fingers, counters or pebbles then being placed in the grooves. Those placed in the first grooves represented units ; in the second tens ; and so on. In counting, as soon as ten pebbles had been placed in the first groove, they were removed and one was added to the second groove. In this way counting could be carried on almost indefinitely.

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[1] The separate grammatical forms for singular, dual, and plural in Greek are perhaps a survival from the same phase of thought.—J. L. M.

Whatever form the abacus takes, it will be obvious that the introduction of colours enables calculations to be made more rapidly. Another device is to have every fifth bead of a different shape. A little consideration will indicate that many other minor improvements are possible in this type of apparatus. That the abacus has played a prominent part in leading mankind to arithmetical levels which might never have been reached otherwise is beyond dispute. Even the Greeks, who took the empirical methods of earlier nations and out of them developed an abstract science, fell back in arithmetical calculations upon the abacus and a multiplication table learnt by heart.

Directions for Knowing all Dark Things

Geometry originated in the purely practical need of restoring boundaries in Egypt and Babylonia after periods of inundation. When boundaries were swept away there would no doubt be considerable dispute between neighbours, and some method would have to be evolved for adjusting the claims made. Hence the necessity for surveying, which in turn led men to devise a number of formulæ for determining the areas of irregularly shaped fields.

In addition to the measurement of superficial areas it was important to find some method for determining levels. For unless relative levels were known it would be impossible to ensure that the water was distributed to the advantage of all. The Egyptians gave much attention to these matters, but it is clear that they never got very far in the development of their geometry. They acquired isolated scraps of knowledge—they devised a method for drawing a hexagon, for example, but not a pentagon—but their formulæ were entirely empirical and their results for the most part only approximately correct.

In order to draw one line at right angles to another on the ground, or erect one line perpendicular to another, it was common practice from very early times to make use of professional "rope-stretchers." These men were aware that if the sides of a triangle are in the ratio of 3 : 4 : 5, then it must be a right-angled triangle. They therefore provided themselves with a rope divided by knots into lengths in this ratio, and by stretching the rope over pegs inserted at the knots it was only necessary to bring the ends of the rope together to obtain a right angle. A similar method is sometimes adopted by mechanics at the present day.

Our knowledge of ancient Egyptian geometry and arithmetic is based very largely on a papyrus written by a scribe named Ahmes, who is believed to have lived about 1700 B.C. Ahmes entitled his work : *Directions for Knowing All Dark Things.* That part of the papyrus which he devoted to geometrical problems is concerned with methods for finding the areas of circular fields, the cubic contents of barns, the areas of various rectilinear figures, and with processes for finding dimensions which could not be ascertained by direct means. Generally speaking Ahmes appears to have been content if he could get a result which was sufficiently correct for ordinary practical purposes. His calculations relating to the area of circular fields led him to a formula which was equivalent to giving π a value of 3·1604. In this he at least achieved greater accuracy than the Babylonians and the Jews, who appear to have reckoned that the circumference of a circle was three times the length of its diameter.[1]

In another part of his papyrus Ahmes discusses the summation of fractions, a primitive kind of multiplication which involved repeated additions, and the solution of various numerical equations. Two problems with which he concludes involve arithmetical progressions.

A reasonable degree of accuracy in simple land surveying must have been reached in Mesopotamia as early as the beginning of the third millennium B.C. In the British Museum there are Babylonian survey tablets dating back to about 2300 B.C. Some of these comprise lists of fields or estates, each tablet giving measurements and other particulars of fields.

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[1] See, for example, 2 Chron. iv, 2.

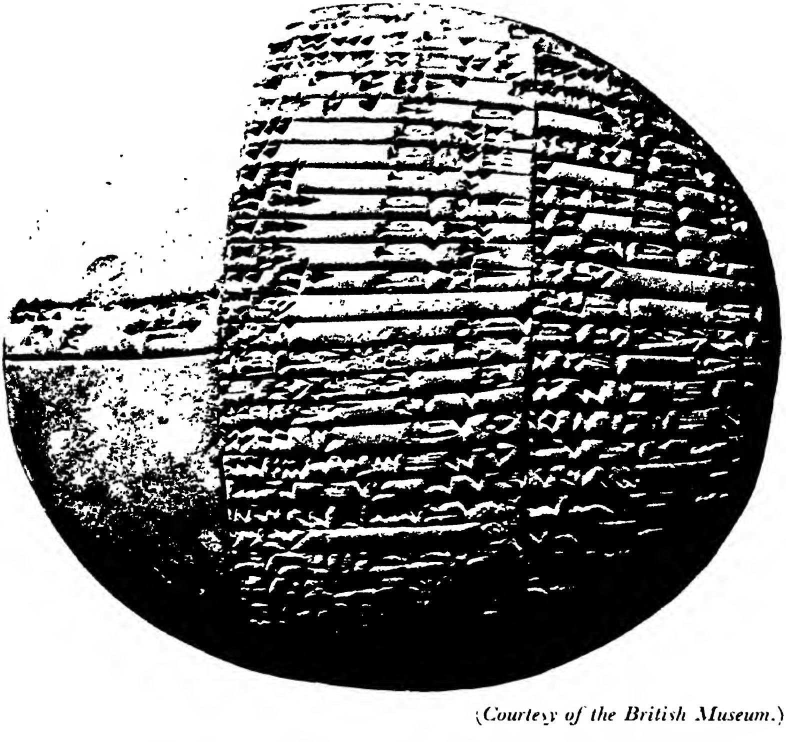
The fields being in many instances of irregular shape, their area is calculated by reckoning them as forming rectangles or regular figures, and then adding to or subtracting from this area such parts of the field as lie outside or inside these lines. The result is an approximation to the area of the field. Where the field is measured on three sides, the area is obtained approximately by multiplying half the sum of two sides by the other side and then proceeding as before.

Despite claims made on their behalf it is doubtful whether either the Chinese or the Hindus made any notable contribution to geometry prior to its development into a science by the Greeks.

3

Market Place and Counting House

Four thousand years ago or thereabouts an Egyptian sold a bull for one mat, five measures of honey, eleven measures of oil, and seven other objects of different kinds. A record of this particular transaction happens to have been preserved, but of course similar exchanges were taking place all over the civilised world. In Asia Minor, for example, the interchange of goods had reached such a scale at this time that banking houses were found necessary to finance it. On these banks the merchants were dependent who organised the extensive caravan trade which passed to and fro along the Royal Road and other routes radiating from Cæsarea Mazaca. The bankers kept numerous scribes busy in their counting-houses, making records many of which have also been preserved. Banking firms were also established in Babylonia. One of these, Egibi and Sons, carried on business from an unknown date down to about the 4th century B.C. The code of Khammurabi, compiled about 1900 B.C. and probably based on earlier codes, gives us several glimpses of the trading relations of those times. Thus : " If the merchant has given to the agent corn, wool, oil or any sort of goods to traffic with, the agent shall write down the price and hand over to the merchant ; the agent shall take a sealed memorandum of the



(*Courtesy of the British Museum.*)

List of fields or estates with measurements and statistics. About 2220 B.C.

[*To face p.* 96.

price which he shall give to the merchant." And again: " If an agent has forgotten and has not taken a sealed memorandum of the money he has given to the merchant, money that is not sealed for, he shall not put in his accounts."

Once men get beyond the primitive stage of considering only their immediate requirements, they become producers of goods which they do not themselves intend to consume. No longer entirely concerned with their own needs, they are thereafter guided by the requirements of the market; and to the market they repair with their products, only retaining enough to satisfy their own needs. Now the very conception of a market implies a continual interchange of commodities; an interchange in which he who is the readiest reckoner would normally come off best. Even primitive barter would be difficult without some idea, however vague, of enumeration, addition and subtraction. The difficulties presented by fractions would be experienced at a very early stage. Thus, quite apart from calculations necessitated by the inundations, men would find in trade a strong inducement to exercise their minds on simple arithmetical problems.

Both market-place and counting-house would also lead to the idea of standards against which measurements of weight, volume, area, length and so forth could be checked. At the time of the Egyptian transaction already quoted it was the practice to sell articles by weight, and public weighers were appointed to determine the value of goods in relation to pieces of copper, silver or gold. Scribes were in attendance to make records of exchanges, quantities and weights. The pieces of metal, which were in circulation in the form of bricks or—more usually—rings, were also weighed like any other commodity. There was no coined money as yet; nor, so far as we can tell, had men begun to bemuse their wits with the notion of a " standard " of value, gold or otherwise. Had some bright scribe like Ahmes thought about the matter at all in those days, when metals were used as a means of exchange solely because they were relatively portable and easy to divide, he would probably have realised—what countless millions of men have failed to realise since—that value is an accidental relation between things; and can no more be the property of any one thing than an angle can be the property of one straight line, or a rate the property of distance without time.

Standards of weight, volume and linear measurement, however, are a very different matter; and it is scarcely necessary to stress the importance of this new step in man's mental development. Without standards engineering would doubtlessly have continued to develop as an art, but it could never have become a science.

The activities of trade were linked up with those of the rope stretchers and other surveyors in various ways, notably through the complicated business of taxation. Rectification of boundaries after the inundation was a matter of importance to the Egyptian fiscal authorities as well as to those who owned or who were employed on the land. The central finance department was controlled by a Lord High Treasurer, "Governor of all that exists or does not exist," and under him was an army of officials including scribes and surveyors. The surveyors made frequent surveys of the territory belonging to the various towns and rural districts, after which their calculations were turned over to the scribes for the assessment of land taxes. This no doubt explains why the most elaborate mathematical treatise which has come down to us from pre-Hellenic times was the work of an Egyptian scribe.

4

Stars and Seasons

The earliest endeavour to establish some form of calendar, by which the seasons and the passage of time could be measured and recorded, was made long before the dawn of history. When men settled down to an agrarian existence they must have frequently felt the need of such a device. Those who guessed that it was the same sun which returned day after day, who noticed certain peculiarities about the relative movements of heavenly bodies, and observed the rhythmic recurrence of the seasons, would be led at length to experiments in chronology. Some authorities believe that the Egyptians had made sufficient observations and records to arrive at a calendar by 4241 B.C., and the Sumerians possibly by an even earlier date. And with this business of devising a calendar went a complex of religious motives and superstitions which led men in all lands to build up elaborate "sciences" of astrology.

The mind of man turns perennially to the thought of how he may evade the normal evils of existence; bad weather, spoilt crops, famine, accidents, pain, disease, death. Can these evils be evaded by means of spells and prayers? Is it possible that they are somehow influenced by the departure, return and relative motions of the sun, moon and stars? Early man at least had no doubts on these matters. With remarkable unanimity, all peoples from China to Peru have believed that celestial bodies were animated by powers which, under favourable circumstances, could be controlled or propitiated by suitable rites and sacrifices. It became therefore of the utmost importance to study omens, to devise spells, and above all to predict the movements of these celestial bodies by calculation, so as to ensure maximum potency by the performance of ritual at the due time.

Out of such unpromising material came a variety of mathematical formulæ which were used in connection with finding a fixed number of months to coincide with the cycle of the seasons; observing and recording the heliacal rising of certain stars in order to arrive at the true length of the solar year; the business of making a lunar calendar agree with the true year so observed by the intercalation of additional days or even an extra month from time to time; and so forth. The prediction of eclipses also was an important matter. According to Chinese historians an eclipse of the sun occurred during the reign of Chung-Kang (2159–2147 B.C.) when two court astronomers, Hi and Ho, were decapitated for having failed to predict it. They were said to have been partaking in a carousal at the time instead of attending to their duties. Carousals appear to have been a common failing with the astronomers of ancient China, one of these functionaries having on another occasion seriously affirmed that he had seen two suns in the sky at the same time ! It is interesting to note that both Chinese and Assyrian astronomers recorded eclipses of the sun which occurred in the 8th century B.C. The accuracy of these records has recently been confirmed by European astronomers. The event in China was commemorated in verse, of which the following is an extract :

" For the moon to be eclipsed
Is but an ordinary matter.
Now that the sun has been eclipsed,
How bad it is !
Alas for the men of this time !
Why does the King not stop these things ? "

The Babylonian and Assyrian astronomers made continuous observations, calculations and records. The Egyptians also were astronomers of considerable ability, while in India astronomical observations and records began at least as early as the period in which the *Rig-Veda* was written.

And while the civilisations of the Old World were thus contributing to the growing fund of elementary mathematical knowledge, an isolated race far away to the west—in a land so remote and inaccessible that it might have been on another planet—was passing through archaic phases of culture. We know this people now as the Mayas of Central America. They, too, were much preoccupied with astronomical calculations, eventually reaching an extraordinary degree of efficiency in this regard. Such indeed was their outstanding mathematical ability among primitive civilisations, that they invented a system of place-value numeration, an equivalent of our decimal system, a thousand years before this important mathematical device was known to any of the civilisations of the Old World.[1]

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[1] The Babylonians evolved a notation which in some respects resembled a decimal system. Archimedes also appears to have had a glimpse of the possibilities of such a system. The so-called "Arabic" numerals, including the zero, may have been developing as early as the 4th century A.D., though the earliest known examples of the zero are 9th century A.D. Diffusion westward was largely due to al-Khwarizmi (Muhammad ibn Musa) in the latter century.

CHAPTER VIII

ENGINEERING IN GRAECO-ROMAN ANTIQUITY

I

A Note on Greek Science

It would be beyond our scope to discuss in any detail the brilliant speculations of Greek philosophers and men of science. All that we shall attempt here is to emphasise that these speculations bear witness to a new way of thinking, destined to modify profoundly the relations between man and his environment ; and that this new way of thinking was not so entirely divorced from practical applications as is sometimes supposed. We shall also note in passing that concurrently with this development also came the first clearly recorded attempts in the whole history of the human race to harness the forces of Nature " for the use and convenience of man "—apart, that is, from the use of wind for sailing ships.

We have seen that a preliminary groundwork of elementary mathematics and astronomy had already been prepared by the older civilisations of Egypt and Mesopotamia. This also is true of science in general. The crude beginnings of medical, chemical, mechanical, and physical sciences were already in existence long before the Greeks began to speculate about these matters. But the point to note is that while their predecessors had been content with isolated fragments of empirical knowledge, it remained for the Greeks to give rational explanations of natural phenomena, and to show that by the guidance of first principles and logical reasoning, seemingly independent events might be linked together into an orderly system of cause and effect.

It is true that Egyptian and Babylonian " scientists " sometimes made use of a kind of logic ; but it was the logic of nightmare. Like most primitive races they seem to have been shadows and mysteries, ominous and alive with baffling powers. These powers had to be overcome by incantations, propitiated by ritual and sacrifice. Otherwise in their malignity they might swoop down on you out of the howling gale, the lightning flash, or the starry dome of night. In such an atmosphere events depended not on natural causes but on the volition of countless supernatural beings. As already intimated, it was the triumph of the Greek mind that it was able to visualise a world in which results follow from natural causes which, given sufficient knowledge, are ascertainable by strictly logical reasoning processes. " Let us first understand the facts," said Aristotle, " and then we may seek for a cause."

It is frequently said that Greek philosophers and men of science almost universally held with Plato that it was undignified to put one's knowledge to practical uses. There is, however, considerable evidence to the contrary. Thus, there was a legend in the time of Herodotus that Thales—the father of Greek science—was employed on military engineering work. And though this may have been no more than legend, yet the very fact that such stories were current indicates that the notion of a philosopher turning his gifts to practical ends was not held to be altogether improbable.[1] Again, the astronomer Harpalus supervised the construction of bridges for Xerxes. Another astronomer, Meton, designed and erected in the streets of Athens a large almanac, with movable bronze tablets carrying the names of the months and the numbers of days in the changing civil calendar. Philon of Byzantium wrote a treatise, with mathematical calculations, on the construction of catapults and other military engines ; describing huge cross-bows which were put under tension by a windlass, and would shoot arrows six feet long ; also giving an account of a very effective torsion machine-gun. Archytas is said to have experimented with mechanical flight, while Ctesibius we know was responsible for the design of a practical force pump, also an equally practical and useful water clock. Heron of Alexandria[1] designed a small reaction steam turbine or " whirling eolipile " to which we shall refer again in Book II. He also, among other contrivances, described an ingenious coin-in-the-slot machine, a taximeter for measuring and recording the distance covered by wheeled vehicles, organs operated by water and compressed air, all indicating that his scientific researches did not prevent him from making extensive acquaintance with practical mechanics. Pappus discussed a mechanical device in which a cogwheel with oblique teeth moved on a cylindrical helix ; what we should now call worm gearing. Archimedes is said to have invented or improved the screw or spiral for raising water ; the compound pulley ; a planetarium operated by water ; and burning glasses for setting enemy ships on fire—a feat long afterwards proved to be possible by Buffon, who set planks of wood on fire at a distance of 200 feet by similar means.[2] So we might continue with a long list of other mechanical and kindred contrivances invented or adopted and improved by Greek philosophers and men of science.

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[1] See also Aristotle (*Politics*, I, 11) for an entertaining story of Thales and " applied science." Other men of the 6th century B.C. noted for practical ability were Anacharsis, Glaucus, Chersiphron, Metagenes, Theodorus, Eupalinus, and Mandrocles.

It may be remarked that apart from mathematics and astronomy the Greeks made no very striking progress in science. As Mr. W. W. Tarn says in his book, *Hellenistic Civilisation :*

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incapable of realising that effects must necessarily have something in common with the causes which produce them ; that events are governed by laws which can be established by observation and rational deduction. As we have noted, they lived rather in a world where occult powers were constantly interfering with the normal course of events. Such progress as they made was not due to rational thinking but to intuition and the lessons of practical experience. All about them were shadows and mysteries, ominous and alive with baffling powers. These powers had to be overcome by incantations, propitiated by ritual and sacrifice. Otherwise in their malignity they might swoop down on you out of the howling gale, the lightning flash, or the starry dome of night. In such an atmosphere events depended not on natural causes but on the volition of countless supernatural beings. As already intimated, it was the triumph of the Greek mind that it was able to visualise a world in which results follow from natural causes which, given sufficient knowledge, are ascertainable by strictly logical reasoning processes. " Let us first understand the facts," said Aristotle, " and then we may seek for a cause."

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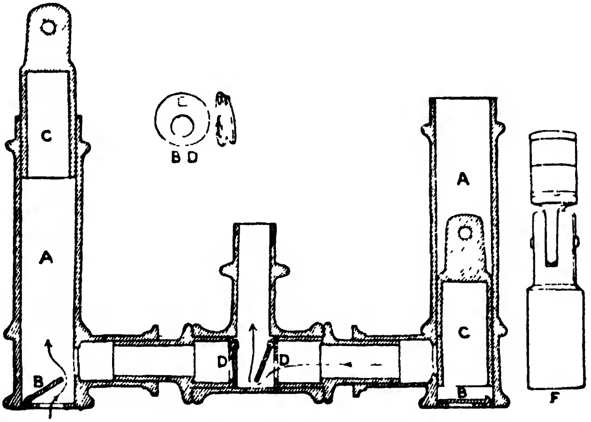
" Of the two sciences which to-day bulk so large, physics and chemistry, chemistry never got started and physics died with Strato." It is suggested that this was primarily due to lack of scientific instruments ; and, adds Professor Myres, " especially the lack of good glass, to enable a man to see what was going on inside a vessel, and to permit experiments with corrosive reagents." Similarly we suggest here that not philosophical prejudice so much as lack of instruments of precision—combined with a plentiful supply of cheap labour—explains why greater progress was not made in practical mechanics.

2

Inventions and Discoveries

We shall not attempt to decide how far the mechanisms attributed to various Greek philosophers were novel, and how far inherited from earlier civilisations. It will suffice to point out that while more than one writer acknowledged his indebtedness both to his contemporaries and his predecessors, it is not unreasonable to assume that the Greeks made notable additions



Section of Roman bronze pump, now in the British Museum.
A, Cylinders. C and F, Plungers.
B and D, Flap-valves. BD, A valve.

and improvements even when they were not themselves the actual inventors of the devices which they describe.

It is probable that of the various inventions attributed to Ctesibius, the force pump was by far the most generally useful. It was described by Heron and also by Vitruvius. Bronze pumps, found at Bolsena, Etruria, and now in the British Museum, fit the description given by the Greek and Roman authors so closely that they must clearly have been made on the lines laid down by Ctesibius.

Vitruvius tells us that the

> " machine of Ctesibius, which raises water very high, is made of bronze, and has at the bottom a pair of cylinders set a little way apart. There is a pipe connected with each, the two running up, like the prongs of a fork, side by side to a vessel which is between the cylinders. In this vessel are valves, accurately fitted over the upper vents of the pipes, which stop up the vent holes, and keep what has been forced by pressure from going down again.
>
> " Over the vessel an inverted funnel is fitted, and fastened to the vessel by means of a wedge thrust through a staple, to prevent it from being lifted off by the pressure of the water which is forced in. On top of this a pipe called the *tuba* is arranged vertically. Valves are inserted in the cylinders, beneath the lower vents of the pipes, and over the openings in the bottoms of the cylinders.
>
> " Pistons smoothly turned and rubbed with oil, being inserted in the cylinders from above, work with their rods and levers upon the air and water in the cylinders ; and, as the valves stop up the openings, force and drive the water, by repeated pressure and expansion, through the vents of the pipes into the vessel from whence, rising to the top, the air presses it upwards through the pipe." [1]

Pumps similar in design to this have been used down to quite recent times for putting out fires. The fact that, when Vitruvius wrote his description, it was apparently the custom to turn the pistons, throws an interesting sidelight on the technique of Roman engineers. The pistons were presumably turned in a lathe, though owing to incrustation and corrosion the specimens in the British Museum throws very little light on this point.[2]

The coin-in-the-slot machine described by Heron is simple but ingenious. It was used by Egyptian priests for the sale

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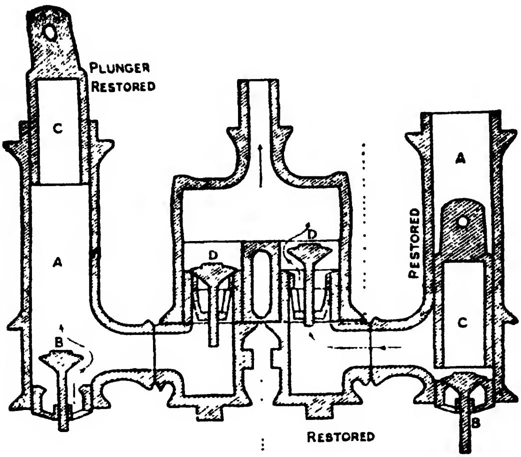
[1] Vitruvius, *Ten Books on Architecture*, Book X, Chapter VII.

[2] Heron refers to vessels bored in a lathe to fit a piston.


PLUNGER
RESTORED
C
A
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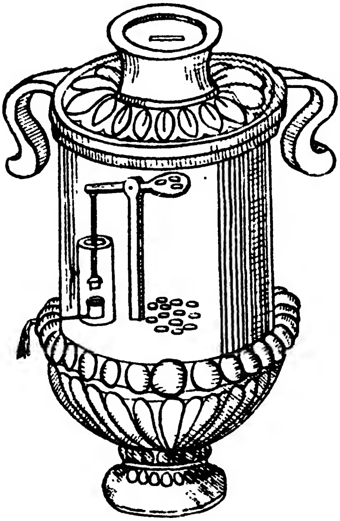
Section of second Roman pump in the British Museum.
Note the improved " mushroom " type of valve.



Coin-in-the-slot machine, *c.* 1st century A.D.
From Giorgi's translation of Heron's *Pneumatics*, 1592.

of holy water. In the example illustrated, coins to the value of five drachmæ had to be inserted before any of the purifying water came out, though more coins could be put in if desired. Referring to the illustration, a vessel in the shape of a closed vase was provided with a slot at the top. Within the vessel was a cylinder containing a supply of holy water. From the bottom of this a tube passed through the wall of the containing vessel to a point at which water is discharged. In the bottom of the cylinder, controlling the flow of water to the tube, was a valve attached to a vertical rod, the upper end of which was connected to a horizontal lever. The other end of the lever carried a flat dish on to which the money fell when placed in the slot.

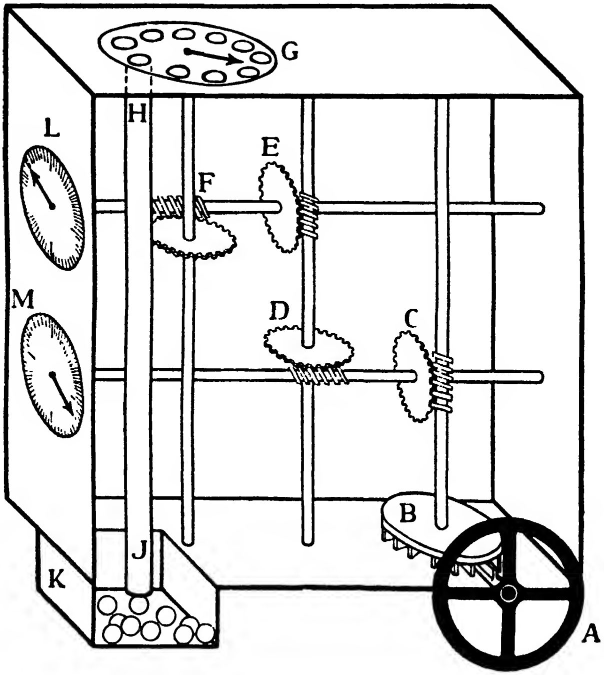
Normally the weight of the valve rod kept the valve closed ; but when sufficient coins were inserted they depressed the lever and raised the valve. A small quantity of liquid then escaped, but as the dish became inclined from its horizontal position the money would slide off, the valve would close, and the apparatus would then be ready for the next customer. It might be argued that this mechanism served no " useful " purpose ; but that would be entirely to misunderstand the mentality of the Egyptian people, whose whole existence was dominated by religious considerations.

The taximeter of classical times, first mentioned by Heron, is described in a slightly modified form by Vitruvius as follows :

> " The drift of our treatise now turns to a useful invention of the greatest ingenuity, transmitted by our predecessors, which enables us, while sitting in a carriage on the road or sailing by sea, to know how many miles of a journey we have accomplished. Thus, let the wheels of the carriage be each four feet in diameter, so that if a wheel has a mark made upon it, and begins to move forward from that mark in making its revolution on the surface of the road, it will have covered the definite distance of twelve and a half feet on reaching that mark at which it began to revolve.
>
> " Having provided such wheels, let a drum with a single tooth projecting beyond the face of its circumference be firmly fastened to the inner side of the hub of the wheel. Then, above this, let a case be firmly fastened to the body of the carriage, containing a revolving drum set on edge and mounted on an axle ; on the face of the drum there are four hundred teeth, placed at equal intervals, and engaging the tooth of the drum below. The upper drum has,

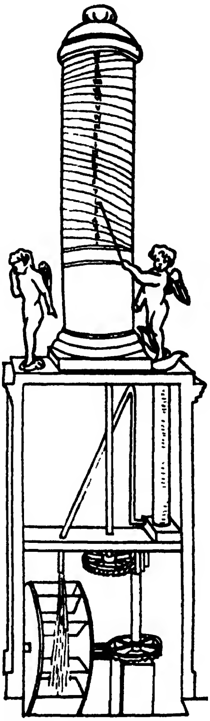
moreover, one tooth fixed to its side and standing out farther than the other teeth.

" Then, above, let there be a horizontal drum, similarly toothed and contained in another case, with its teeth engaging the tooth fixed to the side of the second drum, and let as many holes be made in the third drum as will correspond to the number of miles that a carriage can go in a day's journey. Let a small round stone be placed in every one of these holes, and in the receptacle or case containing that drum let one hole be made, with a small pipe attached. Through this, when they reach that point, the stones placed in the drum will fall one by one into a bronze vessel at the base of the taximeter.



Taximeter of Vitruvius. From *The Mechanical Investigations of Leonardo da Vinci*, by Ivor B. Hart.

" Thus as the wheel in going forward carries with it the lowest drum, and as the tooth of this at every revolution strikes against the teeth of the upper drum, and makes it move along, the result will be that the upper drum is carried round once for every four hundred revolutions of the lowest, and that the tooth fixed to its side pushes forward one tooth of the horizontal drum. Since, therefore, with four hundred revolutions of the lowest drum, the upper will revolve once, the progress made will be a distance of five thousand feet or one mile. Hence every stone, making a ringing sound as it falls, will give warning that we have gone one mile. The number of stones in the bronze vessel will show the number of miles in the day's journey."[1]



Water-clock of Ctesibius. From Perrault's transla

Vitruvius also describes a method of adapting the mechanism to a ship. Heron's taximeter was equipped with graduated dials over which pointers passed rather as in a modern gas meter. It would appear that Heron's mechanism was more exact, but less practical than the other. The principle of the modern taximeter is not very unlike that indicated by Vitruvius.

So far as can be ascertained from various sources, one of the water-clocks of Ctesibius consisted of a cylindrical column placed on a square pedestal, within which the mechanism was concealed. The hours for both day and night were marked upon the column; their inequality at different seasons, as indicated by a sundial, being measured by unequal distances between the curved lines and by the revolution of the column round its axis once a year. On the pedestal are seen the figures of two boys, one of which was immovable, but the other rose and pointed out the different hours with his wand. Water (supplied from a reservoir by a concealed pipe) continually dropped from the eyes of the figure on the left, and falling into a dish was conveyed, by a horizontal channel, under the feet of the other figure; where it trickled into a deep vessel, or a large vertical tube, whose lower end was closed. In this tube a float was made to rise and fall with the water, and being attached to the feet of the figure with the wand, caused it to rise also and so indicate the lapse of time. At the end of twenty-four hours the tube would be filled, and the figure reached the top of the column. The syphon shown in the illustration then came into play. Its short leg was connected to the lower part of the tube containing the float and its bend reached as high as the upper end of the tube. When the latter was full, the syphon would be charged, and the contents of the tube would be run off by it into one of the buckets of the wheel, also shown. The figure with the wand would then descend, having nothing to support it. The wheel, having only six buckets, revolved once in six days. To its axis was secured a pinion of six teeth meshing with a wheel with sixty ; and on the shaft of this wheel a pinion with ten teeth meshed with a wheel having sixty-one. This last wheel turned the column round once in 366 days. As the accuracy of the clock depended on the size of the orifices in the weeping figure, Ctesibius bushed them with jewels to reduce wear.[1]

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[1] Vitruvius, Book X, Chapter IX. Translated by M. H. Morgan.

The German author, Hermann Diels, gives in his *Antike Technik* a description of an alarm clock said to have been used by Plato to waken his disciples in the morning. Water trickles from one vessel into another. When after the required lapse of time the second vessel is full, its contents are suddenly emptied by syphonic action into a third. The air in this third vessel is compressed, and rushing out through a tube, blows a whistle. The principle of the syphon, it may be added, was known to the Egyptians at least a thousand years before the time of Plato.

In Philon's torsion machine-gun, to which we have already referred, there is a solid rotating cylinder containing a groove just large enough for one arrow. Into this groove an arrow falls from a receptacle directly above. The cylinder rotates, taking the arrow with it. A point is reached where the arrow groove in the rotating cylinder is directly over another arrow groove in the shooting mechanism, and at that moment the arrow is transferred from one to the other. The slot on the rotating cylinder, now empty, passes on ; until, reaching the receptacle at the top again, another arrow falls into it.

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[1] See Ewbank, *Hydraulics and Mechanics*, p. 546.

One man operates the whole of the mechanism by turning a handwheel. This is connected by an endless chain to the rotating cylinder, and to a " finger " or trigger which puts tension on the string. A turn or two of the wheel pulls back the trigger and—rotating the cylinder at the same time—brings an arrow into position. A further turn of the handwheel releases the trigger, the arrow is fired, and the cylinder makes another half-revolution ready to receive another arrow. Thus the processes are repeated and a continuous fire is kept up until all the arrows in the receptacle are used. The driving power was, of course, derived from the elasticity of the material selected for the bow.

Here, then, we have a few of the highly ingenious devices, the earliest known records of which were made by writers of Græco-Roman times. Another invention, the water-wheel, is of such special significance that we must leave it until we discuss the early use of external power in Book Two. Besides recorded inventions, it should be understood that there were in all probability many others of which we have no written evidence. " There are innumerable ways of employing machinery," says Vitruvius, " about which it seems unnecessary to speak, since they are at hand every day ; such as mills, blacksmiths bellows, carriages, gigs, turning lathes and other things which are habitually used as general conveniences." What would many of us not give now for detailed descriptions of the " turning lathes and other things " which this Roman engineer and architect dismissed as being commonplaces of his time ?

3

Civil Engineering in Ancient Rome

As every reader knows, the Romans made remarkable progress in civil engineering. Their aqueducts, drainage systems, roads, bridges, and other constructions, taken as a whole, reached a pitch of perfection which was without precedent.[1]

In and about the city of Rome there were at one time some 250 miles of aqueducts, not less than fifty miles being supported on stone arches. The chief source of information on this subject is a treatise by the Roman engineer-architect Frontinus. Other particulars may be gleaned from Pliny's *Natural History*, Book XXXVI., Chap. 24.

The aqueducts of Rome were built owing to the need for better supplies of water than were afforded by the Tiber and the various wells in the city. There were nine of these conduits in existence at the time Frontinus compiled his treatise, each of the nine streams of water entering the city at a different level from the others. The Aqua Claudia and the Anio Novus were the most expensive and impressive of these works. Some of the arches supporting the Anio Novus were over 100 feet high. It has been calculated that the total amount of water delivered by the nine aqueducts was equal to a stream 20 feet wide by 6 feet deep, ceaselessly pouring into Rome a volume of water equivalent to over 300,000,000 gallons a day.

Many other aqueducts were built by the Romans in various parts of the Empire. It is sometimes asked why the Romans did not adopt the principle of the syphon, with which they were familiar, instead of going to the trouble and expense involved in building these enormous stone structures. The answer is that of the available alternatives, the Romans were not prepared to rely on concrete and cement for keeping the syphon airtight, and lead pipes would have been far too costly for general use on a large scale. It is also highly probable that the technique of the time was barely equal to constructing large metal pipes strong enough to stand the pressure. One of the few exceptions where lead syphons were used is to be found in the aqueducts at Lyons.

Rome has been described as a city suspended above a network of navigable sewers. The most impressive remains of the Roman drainage system are those of the Cloaca Maxima, a main drain so large that it would be possible to drive a loaded haycart through it. The interior dimensions average about 14 feet high and 11 feet wide ; and the roof is supported by three concentric arches formed of blocks of stone 5½ feet long, fitted together without cement. The solidity of the whole structure is remarkable.

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[1] And, until the 19th century A.D., only approached by the roads, aqueducts and stone structures of the Inca engineers and their predecessors in old Peru.

The vast labour and expense bestowed on their public highways by the Romans is a commonplace of history. So important were these " arteries " considered that only men of the highest rank were eligible for the work of superintending their construction. During the empire Augustus himself took charge of them. Most of the roads in the neighbourhood of Rome were paved for a width of about 15½ feet. This part was usually reserved for military purposes. At either side were " margins," each about 8 feet wide, used for foot passengers, horses and carriages. These margins were separated from the paved portion by curbs, 2 feet wide and 18 inches high, which served as seats for travellers. The materials used consisted of stones and cement. In general, any stone which could be conveniently obtained was used. After the line of the road had been set out, materials were extracted from excavations made at the sides and rammed down into a solid and durable foundation with specially made iron rammers. This foundation was usually about 3 feet thick. But in the great military highways a bed was first formed of two courses of flat stones laid in mortar. Over this came rubble, then a third layer formed of coarse gravel and lime, and finally the surface consisting usually of lava or basalt, which was specially selected for its capacity to resist weight and the action of frost.

The bridges of the Romans were remarkable for their massive construction, and for the almost universal adoption of the semi-circular arch. The care taken to ensure permanency in all constructions involving arches is indicated by Vitruvius in a chapter dealing with foundations and substructures.

Other notable works included the construction of harbours, breakwaters and lighthouses. The splendid " pharos " at Alexandria, nearly 400 feet high, was built by Sostratus of

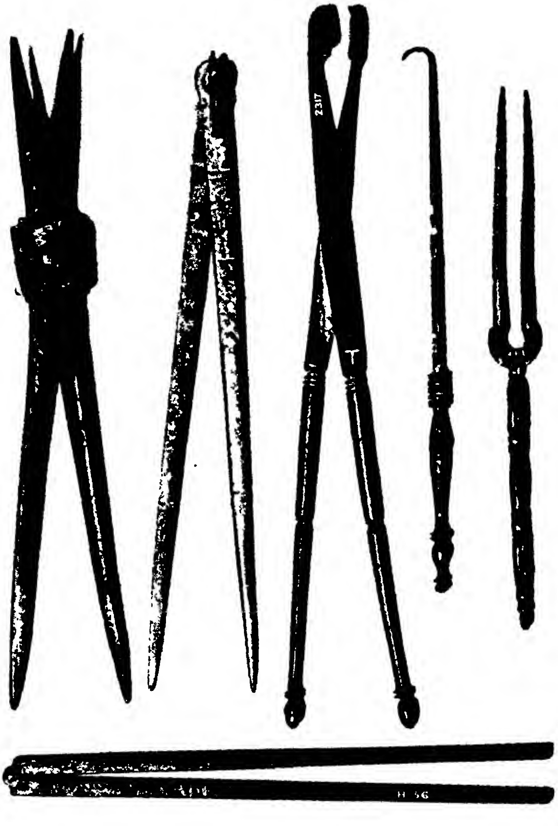
Cnidus, but the Romans erected lighthouses at a number of other harbours, notably at Puteoli, Ravenna and Messina.

Various kinds of lifting tackle were in use in Roman times, multiple pulley-blocks, ropes, the windlass, a primitive kind of crane, and so on. It would appear from a passage in Cæsar's *De Bello Gallico* (IV, 17) that some sort of pile-driving mechanism may also have been used for driving piles for foundations when required. But, of course, all such appliances were operated by hand, or, alternatively, tread-mills. Human muscles, aided a little here and there by those of animals, were still—with one apparently insignificant exception—the only source of power. When we consider the prodigious quantities of stone quarried, shaped, and erected by these early civilisations, the equally prodigious quantities of earth and other materials shifted from one place to another, we get some idea of the interminable hours of drudgery which must have fallen to the lot of the common man. But it was in the mines of Laureion, Cappadocia, Egypt, Ethiopia, and Arabia that the limits of human endurance must have been reached. " There is no indulgence, no forbearance, for the sick, the weakly, the old, or woman's weakness," writes Diodorus. " Under the compulsion of the lash they must all go on working until death puts an end to their sufferings and their distress." According to Agatharcides, the quartz in the Nubian gold mines was dragged out by children, broken up by the older men, and then ground to dust in spar-mills turned not by oxen but by women ; five to a spar, and naked. All were fettered and flogged and worked without rest or care for their bodies. And " all welcomed death when it came."

4

Hand Tools and Instruments of Precision

Most of the common hand tools in use to-day were already known in Græco-Roman times. The carpenter had his kit of planes, bow-drills, saws, chisels, awls, gimlets and rasps. The blacksmith's forge was almost identical with those commonly seen at the present day. The hearth, the bellows,



(Courtesy of the British Museum.)

Roman compasses, dividers, surgical instruments, and folding rule.

the anvil, the hammers, the assortment of tongs for holding hot metal, the smith with his two assistant strikers, are all represented in bas-reliefs of the period. Near by would be the smelting furnace and the foundry. The plumber and the sheet-metal worker plied their useful trades then as now. For the mechanic's shop there were the lathe, the bench and vice, the grindstone, hand drills, files, pincers, and a host of other devices which had been gradually evolved through the ages from the primitive tools of a remote antiquity. It is, indeed, not hand tools which have created such a gulf between ourselves and our predecessors—nor is it even machinery as such. There had always been the human machine. It is *power-driven* machinery which now makes all the difference, including the power-operated tool, and the parallel development on scientific lines of instruments of precision, accurate beyond all comparison with those of the Greeks and the Romans.

If it is true that the science—as distinguished from the art—of engineering had its origins in the invention of instruments for accurate measurement, then we may well regard the water-clock of Ctesibius and the taximeter of Heron as inventions of the highest significance. For between them they pointed the way to entirely new possibilities in the measurement of time and space ; not the least of which was the construction of mechanisms which, besides measuring, could be made to indicate and record.

Among instruments in everyday use for securing some degree of precision were the plummet, set square, water-level, dividers, proportional compasses, foot-rule, measuring rod and measuring chain. For weighing purposes the Romans made considerable use of the steelyard. It seems odd that the Greeks should have only used the simple balance. The Roman steelyard was a well-constructed weighing instrument, showing considerable signs of care in the making. The gnomon, the sundial, and the polos,[1] were used by the Greeks in connection with their astronomical observations. All three were previously known to the Babylonians. Ptolemy seems to have used, or at least known, the planispherical astrolabe, which had probably been invented several centuries before his time.[1] It consisted of a heavy circle of metal so arranged that when it was suspended the divisions which we now call 0 and 180 would come to rest in the same horizontal plane. A bar suspended at the centre of the circle and turning on a pin was furnished with discs containing slots, through which any heavenly body could be seen and its altitude determined in degrees or parts of a degree. Among surveying instruments the chorobates was probably the most important. It consisted of a straight-edge about 20 feet long, supported by legs at the extremities. Crosspieces connecting the straight-edge and legs had vertical lines marked on them, and plummets were suspended so as to hang across these lines. When the straight-edge is in position, and the strings on which the plummets are suspended strike both the lines at the same time, the instrument stands level. Sometimes the straight-edge was provided with a groove filled with water, converting the chorobates into a large water level.[2]

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[1] The polos was a half sphere, hollowed out in stone or metal ; at the bottom a style was fixed with its end reaching to the centre of the sphere. The shadow cast by the style gave an exact representation of the sun's movement.

The mariner's compass is in a sense an instrument of precision, and one that has enormously facilitated the use of external power for ship propulsion. A note on its early history may therefore not be altogether out of place here.

Pliny, Strabo, Lucretius, and other early writers mention loadstone, but not the pole-finding property of a suspended magnet ; and there is no evidence that the mariner's compass was known in Græco-Roman antiquity. The steersman guided his vessel by the Great Bear and the star Cynosura. But the pole-finding property of the magnetic needle may possibly have been known in China in still earlier times, though it must be admitted that there is no reliable evidence. Chinese legend and history relating to this matter are summarised by Hirth in *The Ancient History of China.* Not until we come to the 4th century B.C. do we get definite evidence even of knowledge that loadstone will attract a needle ; while no authentic reference to its pole-finding property can be traced earlier than the 8th century A.D., by which time the eastern deviation of the magnetic needle was also known.

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[1] By Hipparchus of Nicæa.

[2] Vitruvius, *Ten Books on Architecture.*

The earliest use of a suspended magnetic needle appears to have been for geomantic purposes, but by the 12th century it was used on shipboard by foreigners. Navigation on the high seas in the East being then in the hands of Arabs and Persians, these navigators may possibly have adapted the invention to their own purposes, and thus developed it into the mariner's compass. This device had also reached Europe by the 12th century, when it was mentioned by Alexander Neckam. The Arab compass as used by traders in the Levant was a primitive affair consisting of a piece of loadstone, or magnetised iron, floated on cork in a bowl of water. The pivoted magnetic compass was a later development, the earliest known description of this being given by Petrus Peregrinus de Maricourt in his *Epistola de Magnete*, written in A.D. 1269.[1] Peregrinus intimates that the loadstone commonly used was found in northern regions and brought by sailors into the ports of Normandy, Picardy, and Flanders. Because of this it has been suggested that the magnetic compass may possibly have originated with the Viking raiders and traders of the Baltic. But as the Vikings maintained an extensive trading connection with the Arabs and Persians by river routes across Russia in the 9th, 10th, and 11th centuries, it seems more in harmony with all the known facts to assume that they also obtained their knowledge of this invention from the East.

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Postscript to Book One

Here we must close our survey of man's general acquisition of skill during his age-long apprenticeship based on bodily toil. He still had centuries of heavy bodily exertion ahead of him, he still had to become very much more skilled before he could be called an engineer in the modern sense of that word. But we have now discussed his general advancement up to the point at which he began to experiment with external power. Henceforth we must confine ourselves to recording his progress in harnessing the forces of Nature ; progress which was to make heavy demands, directly and indirectly, upon the skill and knowledge which he had taken over half a million years to acquire.

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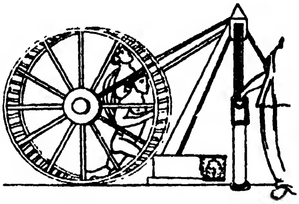
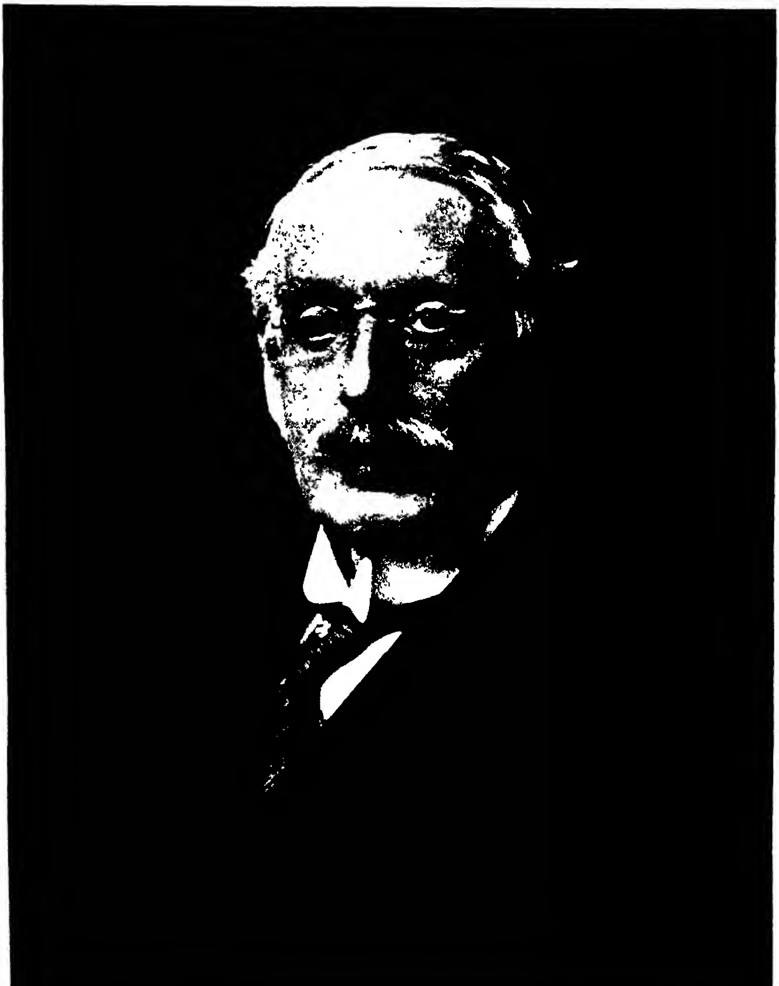
[1] See *Petrus Peregrinus de Maricourt and his Epistola de Magnete*, by Silvanus P. Thompson. Proceedings of the British Academy, Vol. II.





Charles A. Parsons.

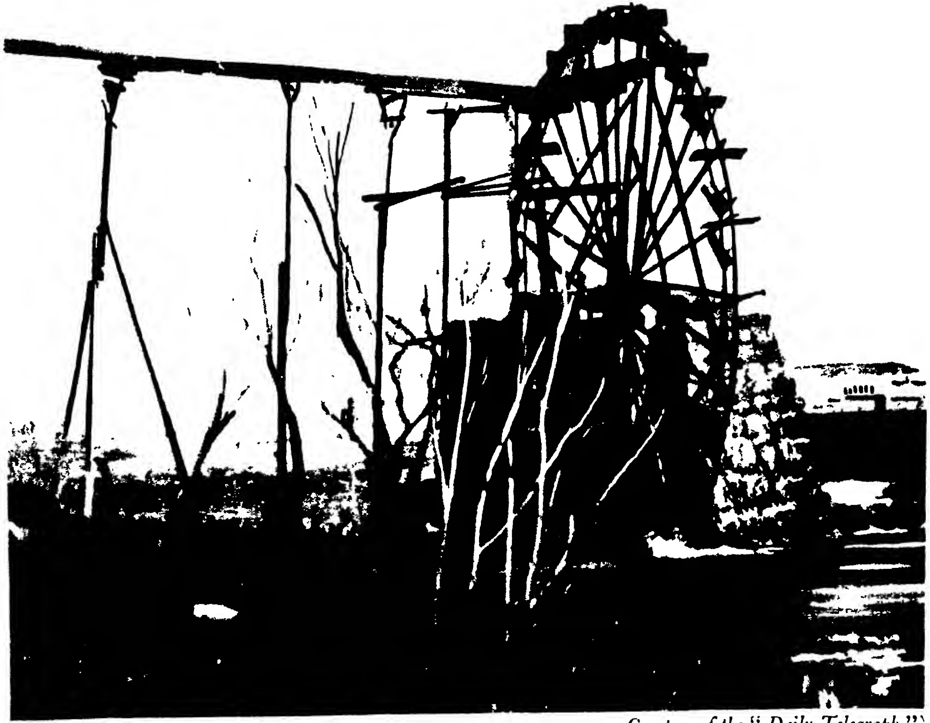
The Hon. Sir Charles A. Parsons, O.M., F.R.S. 1854–1931.

BOOK TWO

THE AGE OF POWER

Out of a million lives our knowledge came,
A million subtle craftsmen forged the means ;
Steam was our handmaid, and our servant flame,
Water our strength, all bowed to our machines."

JOHN MASEFIELD.



(Courtesy of the "Daily Telegraph.")

A water-raising wheel in Syria.

[To face p. 121.

CHAPTER I

THE COMING OF THE STEAM AGE

I

Early Attempts to Utilise External Power

MAN'S progress in the production and application of power may be divided into three stages. We have already followed him through his long apprenticeship of toil, during which he learned to fabricate an ever-increasing diversity of tools and implements, and built up a fund of empirical knowledge. We have likewise seen how in the course of time simple machines and man-power transmitting mechanisms were evolved. During this stage he also made initial experiments in supplementing his bodily powers by pressing animals into his service, and by utilising the wind to propel his ships. Finally, as we shall now see, he entered upon that stage in his career in which he has already acquired an amazing mastery over the forces of Nature, and is yet destined to effect an incalculable reduction in the sum of human labour.

But for centuries after he had begun to use domesticated animals for ploughing and transport, sails for ship propulsion, and perhaps the wheel rotated by the current of a river for water raising,[1] realisation of the possibilities of using external power came slowly. True, he had, as we have already seen, made other discoveries fraught with consequences of the highest import. He had learned how to make and control fire, and to make vessels in which water could be boiled. He knew how to smelt ores and mould metals. But immemorial custom had him in its grip. For countless ages he had eked out a miserable existence. The idea that it was possible to abate the evil of unceasing bodily toil, while at the same time achieving abundance for all, was as yet altogether beyond the span of the human mind.

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[1] The waterwheel turned by the flow of a river was probably in use among the Sumerians. (King, *History of Babylon*, p. 173.) The Sumerians had a month called " The Month for raising Waterwheels."

Apart from such steps as we have indicated, there is reason to suppose that man's earliest experiments in the production and application of external power involved the properties of air and steam. Nevertheless, both waterwheels and windmills were first harnessed to everyday human needs. It will be convenient therefore when tracing the early history of steam to make brief reference to contemporary developments in the use of water and wind.

In Book One we gave particulars of some of the ingenious mechanisms described (if not invented) by Heron of Alexandria, who is believed to have lived in the 1st or 2nd century A.D. Heron's indebtedness to Ctesibius, who himself may have made personal contact with Archimedes of Syracuse, provides scope for much speculation about the origin of these inventions. But this is a line of investigation which we cannot pursue here. Our chief interest in Heron is due to his description of a small steam turbine, in which rotary motion is obtained by introducing steam to a pivoted ball, and then allowing it to escape through two nozzles. The nozzles are arranged so that the ball is whirled round by the reaction of the escaping steam against the atmosphere.[1] Heron's experiments with steam bore no immediate fruit, though after the lapse of some fourteen or fifteen centuries the learning of a poet, and the liberality of a prince, combined with the invention of printing to bring his work to efflorescence. To this we shall return later. Here we must note that while Heron was experimenting with steam at Alexandria, watermills were already being developed and used in eastern Europe. The earliest known reference to such mills occurs in a poem by Antipater of Thessalonica (Salonica), which may be dated approximately at 65 B.C. Strabo also mentions a watermill in Asia Minor which was probably in existence at about the same time. Such mills must have been fairly common objects by the end of the 1st century B.C., since Vitruvius describes them in general terms with water-raising wheels, in his book *De Architectura.* From his description we learn that already at that time power was being transmitted by means of toothed wheels.

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[1] Heron's turbine or " whirling eolipile " was no doubt developed from the ordinary eolipile, which was certainly known in Heron's time and probably long before. Vitruvius, Book I, Chapter VI, describes them as being " hollow bronze balls, with a very small opening through which water is poured into them. Set before a fire, not a breath issues from them before they get warm ; but as soon as they begin to boil, out comes a strong blast due to the fire." The eolipile was used for centuries as a substitute for bellows in blast furnaces and ordinary fires. We give an illustration of an eolipile, used for smelting copper ore, in Book III, Chapter IV, Section I.

The abolition of slavery by the Emperor Constantine, and the conversion by Honorius and Arcadius of free distributions of corn to a daily allowance of bread, must have greatly stimulated the demand for water power for corn-milling purposes. We know that watermills were, in fact, multiplying at Rome under Janiculum. From the Roman poet Ausonius, we learn that water-driven sawmills existed in the 4th century.[1] In the 5th we hear of Anthemius, architect to Justinian, playing elaborate tricks with steam.[2] Then during the dark ages of the western world we find no further reference to steam until we come to William of Malmesbury (*c.* 1095—1143), who records that Gerbert, a monk who afterwards became Pope Sylvester II, constructed a steam-operated organ. As this organ was at Rheims, Gerbert probably made it about A.D. 975—980. There is good reason to believe that he used eolipiles instead of bellows for blowing the organ.

Such is the only evidence regarding man's knowledge of steam which we are able to glean for many centuries. We do know, however, that the use of water power had been steadily expanding all this time. It is just possible that windmills had also come into use. Heron described an apparatus which appears to have incorporated a wheel fitted with vanes rotated by the wind. It is rather odd, however, that the word ἀνεμούριον, which has been translated as "windmill" and

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[1] Ausonius, *Mosella,* lines 361 to 364. The passage runs :

"... ille
praecipiti torquens cerealia saxa rotatu
stridentesque trahens per levia marmora serras
audit perpetuos ripa ex utraque tumultus."

[2] Gibbon, *Decline and Fall of the Roman Empire,* Chapter XL, v.

"sail of a windmill," is apparently unknown in this connection apart from Heron's *Pneumatics*. Strabo mentions two headlands in Asia Minor called Anemourion,[1] the name possibly indicating that windmills stood there at an early date, but more probably (as Eustathius of Thessalonica, writing in the 12th century, seems to imply) simply because these headlands are much exposed to the wind.[2]

Windmills were known in Persia by the 10th century, and according to one account as early as the 7th century. The geographers of the 10th century, Mas'udi, Ebn Hawkal, and Istakhri, all mention the existence of windmills in Seistan, a province in the east of Persia.[3] Many windmills of a very primitive description are still to be seen in Seistan to-day. They are quite different from the European windmill, rotating on a vertical axis and arranged to take the wind from one quarter only. As the wind usually only blows from one quarter in Seistan the arrangement is quite satisfactory.[4]

The Chinese windmill, also rather primitive in design, may be mentioned here. As usually constructed it consists of sails, similar to the sails used on Chinese junks, fitted to a frame which rotates round a vertical axis. The mill operates with the wind blowing from any quarter. Each sail is arranged so that it swivels automatically on its own axis when returning against the wind, taking up a position in which it offers the least possible resistance. The earliest reference to this ingenious windmill that we have been able to trace is that given by Nieuhoff, a Dutchman who accompanied an embassy to China in 1655.[5] Nevertheless, the primitive nature of its construction, and particularly its affinity with the use of sails

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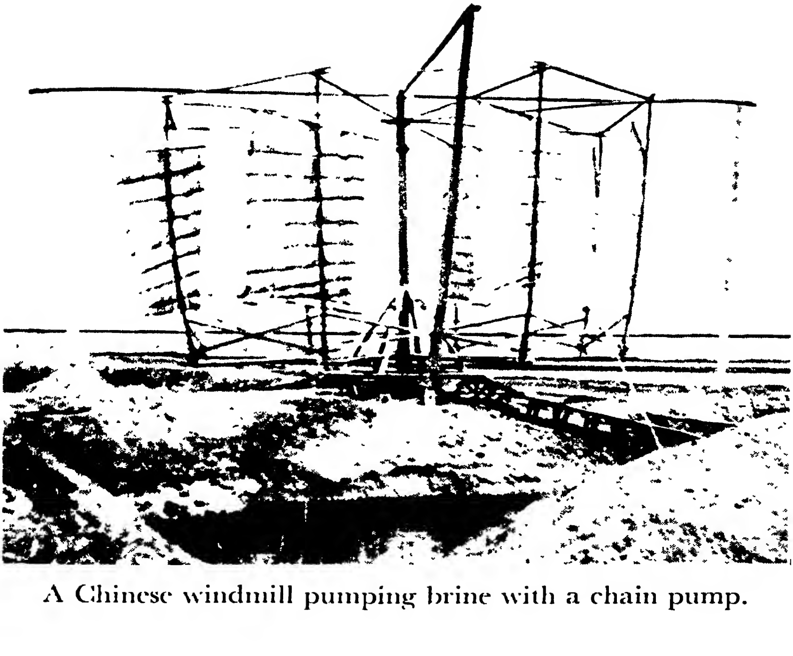
[1] Strabo, XIV, 5.

[2] *Eustathii Archiepiscopi Thessalonicensis Commentarii ad Homeri Iliadem*, Tom. I, p. 222 (Basil. p. 274).

[3] *Les Prairies d'Or*, Vol. 2, p. 80; Vol. 4, pp. 226, 227; also *The Oriental Geography of Ebn Haukal*, Ouseley's translation, p. 205. Istakhri is said to have based his work on that of Ebn Haukal.

[4] Sykes, *Ten Thousand Miles in Persia;* Kennion, *By Mountain Lake and Plain;* and le Strange, *Lands of the Eastern Caliphate*.

[5] "An Embassy from the Netherland East India Company . . . to the Grand Tartar Cham Emperor of China . . . ingeniously describ'd by Mr. John Nieuhoff." The reference to windmills is in Vol. I, pp. 84, 85, with an illustration. These mills are said to have been used for pumping water; to which purpose great numbers are applied in the vicinity of Tientsin at the present day.



A Chinese windmill pumping brine with a chain pump.

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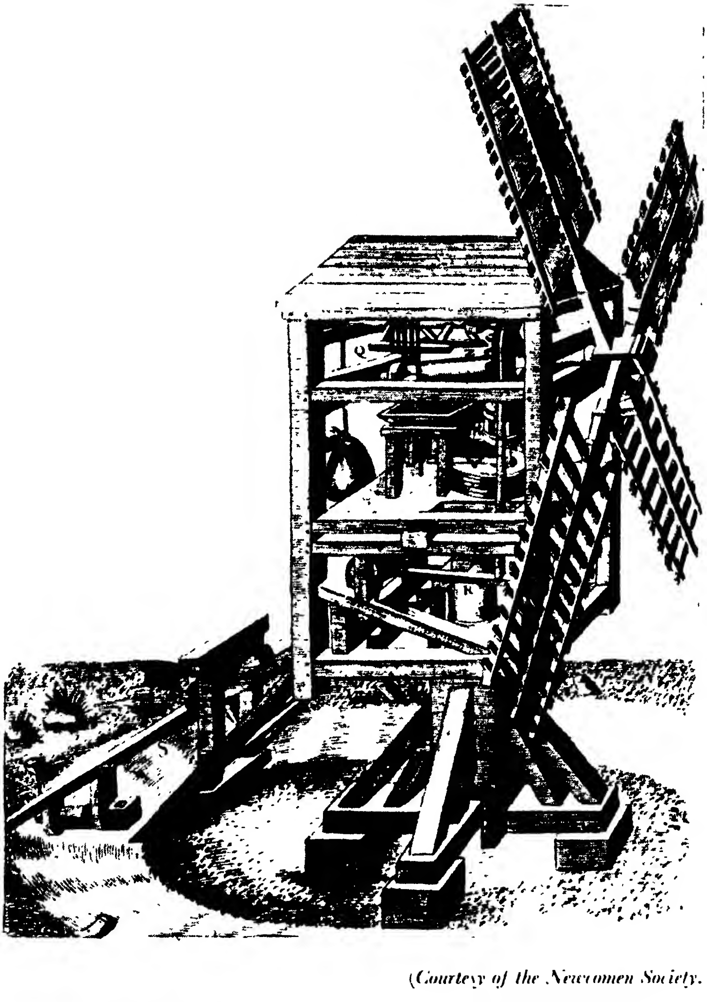

(*Courtesy of the Newcomen Society.*

Post windmill for corn. From Ramelli's *Le Diverse et Artificiose Machine*, 1588.

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for ship propulsion, would appear to indicate that here we may just possibly have one of the earliest methods of obtaining power on land from the wind.

There is no very early evidence of windmills in England. According to Domesday, there were by A.D. 1080 upwards of 5,000 mills in this country; but there is no mention of the windmill as such, nor, indeed, anything to indicate that more than one kind of mill was known at that time. The presumption is that most of the mills mentioned were watermills, though there may have been a few mills operated by cattle where water was not available. The first authenticated date for a windmill in England is A.D. 1191.[1] Within a hundred years or so of that date this method of obtaining power was in general use throughout Europe. Though the European windmill, as stated above, is different in design from those found in eastern countries, it is not improbable that the idea of using wind for power purposes originally came from the East, either by the trade route across Russia already referred to in connection with the magnetic compass, or through contacts with eastern peoples made by the Crusaders; or again, the Arabs who conquered Spain may have brought it with them to Europe, even as they brought much other knowledge of the greatest value to nations whose progress had hitherto been retarded by gross ignorance and superstition.

And now, with only a passing reference to Roger Bacon's knowledge of gunpowder in the 13th century, and the highly significant study of the magnet by his friend, Petrus Peregrinus de Maricourt,[2] we must turn to events which played a notable part in determining the subsequent history of steam. In the 14th century the Italian poet, Petrarch, gave much of his time to the recovery of ancient manuscripts. In the same century Boccacio also applied himself diligently to this task; and, in addition, introduced the study of Greek to Italy. Thereafter many other Italian scholars devoted their lives to the recovery and translation of Greek and Roman manuscripts. To this

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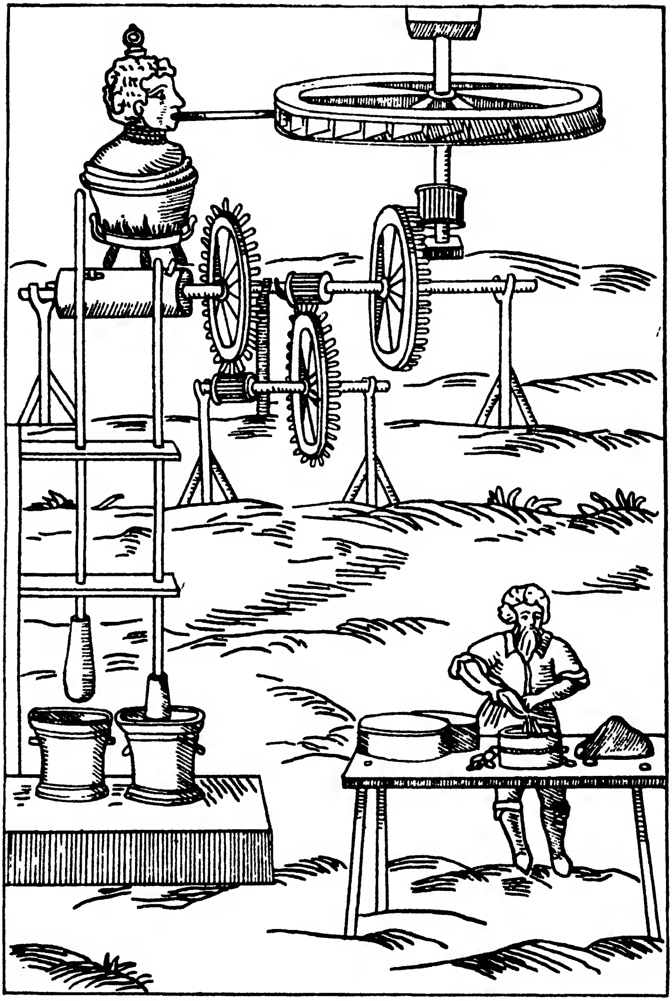
[1] Bennett and Elton, *History of Corn Milling*, Vol. II.

[2] See *Petrus Peregrinus de Maricourt and his Epistola de Magnete*, by Silvanus P. Thompson, F.R.S., in the Proceedings of the British Academy, Vol. II.



Branca's steam wheel, 1629.

movement Cosmo de' Medici afforded every protection and support that prestige, great wealth, and a liberal outlook could give. The invention, or re-invention, of printing with movable type followed in the 15th century, thus leading to the preservation and reproduction of documents which might otherwise have been lost for ever. There can be little doubt that Heron's *Pneumatics* was among the works of classical antiquity thus preserved. The earliest translation appears to have been made by Regiomontanus, the German astronomer and mathematician. Himself a highly skilled printer, he went to Italy in 1461 to learn Greek ; his translation of the *Pneumatics* was not published, however, and it was not until 1575 that the first translation to be printed was made by Frederick Commandine.[1] This was in Latin, and was speedily followed by several Italian versions, whilst new editions and reprints appeared from time to time. It has been well said that thereafter this little book was soon radiating its light all over Europe, stimulating everywhere the spirit of investigation and research. That strange being, Cardan, who "united the most transcendent attainments with the most consummate quackery,"[2] made himself familiar with some of the properties of steam, in addition to drawing up a specification for constructing windmills. Porta, Fludd the alchemist, Decaus, Branca, and Kircher, were all trying experiments with steam or allowing their imaginations to run riot on its possibilities. Branca and Kircher both illustrated wheels rotated by jets of steam, and to the former must be given credit for being the first modern writer to suggest a way of moving solids by steam ; though the arrangement he suggests could have no more worked in practice than his project to flatten bars of steel, by rolls receiving their motive power from a wheel turned by the smoke from a smith's hearth.

Concurrently with this rapidly increasing interest in the possibilities of steam, another highly significant development was taking place. Coal appears to have been worked in Scotland as early as 1200, and imported into London about a quarter of a century later. With the passage of time references to coal become more frequent. When we reach the latter part of Queen Elizabeth's reign we find, for example, that during the seven years 1591—97 the home trade in this mineral increased by about 50 per cent. By 1661 John Evelyn, the diarist, was so impressed by the increasing pollution of London air that he wrote a smoke abatement pamphlet, in which he refers to a " Hellish and dismall Cloud of SEA-COALE " perpetually imminent over London's head, so that " the weary traveller, at many Miles distant, sooner smells, than sees the City to which he repairs." He also expresses concern for some fruit-bearing orchards in the Strand. There can be no doubt that the operations of coal mining—as, indeed, of mining for metals also—must have been extending greatly at this time. With these developments came a new and eventually all-important problem. Mines were liable to be flooded with water. Animals might be used for winding purposes, human beings for winning coal and transporting it underground. But some entirely novel means of coping with water soon became an urgent necessity. It is to be noted that from the time of Queen Elizabeth onwards men of a speculative or inventive turn of mind began to devote attention to this problem. Francis Bacon devised a scheme for raising water from " drown'd mineral works." Porta, Decaus, Kircher, Ramseye, Branca, Prince Rupert, Morland, Worcester, and many others, all considered the problem of water raising, most of them with the aid of steam (or " by fire," as it was commonly expressed in those days), though not in all cases directly concerned with water in mines. In 1663, twenty years after Torricelli made his discovery of atmospheric pressure, the Marquis of Worcester published his *Century of Inventions.* In this book he describes what he calls his " semi-omnipotent engine." Whether Worcester ever made an engine for pumping water, or whether, assuming he did, it was capable of doing all he claimed for it, is a matter concerning which no definite information can be obtained. His description is vague, probably with intention. Men still sought to keep their inventions secret, and gave as little information as possible when recording them. The claims he makes are not altogether extravagant, assuming that he had devised some sort of pumping engine operated by the pressure of steam. He calls it the most stupendous work in the whole world, and refers to it as his wonderful water-commanding engine, boundless for height and quantity, which can be set to drain all sorts of mines and be made to supply power for numerous other purposes. Elsewhere he calls it

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[1] Translations were made of some of Heron's works into Arabic in the 10th century A.D. by Qustā ibn Lūqā of Bagdad. We cannot find, however, that the *Pneumatics* was translated into Arabic at this time.

Greenwood, in his preface to the English translation of the *Pneumatics*, repeats the error of Stuart (*Anecdotes of Steam Engines*, Vol. I, p. 8, footnote) in stating that Aleotti's Italian translation was first published in 1547.

> "an admirable and most forcible way to drive up water by fire, not by drawing or sucking it upwards. . . . But this way hath no bounder, if the vessels be strong enough . . . so that having found a way to make my vessels, so that they are strengthened by the force within them, and the one to fill after the other, have seen the water run like a constant fountain stream, forty feet high ; one vessel of water, rarified by fire, driveth up forty of cold water : and a man that tends the work is but to turn two cocks, that one vessel of water being consumed, another begins to force and refil with cold water, and so successively."

Judging by this account, and from Worcester's reputation for sincerity, we may at least say that here we appear to see the use of steam definitely passing at last from the experimental stage, on to a new plane of practical application to the needs of mankind.

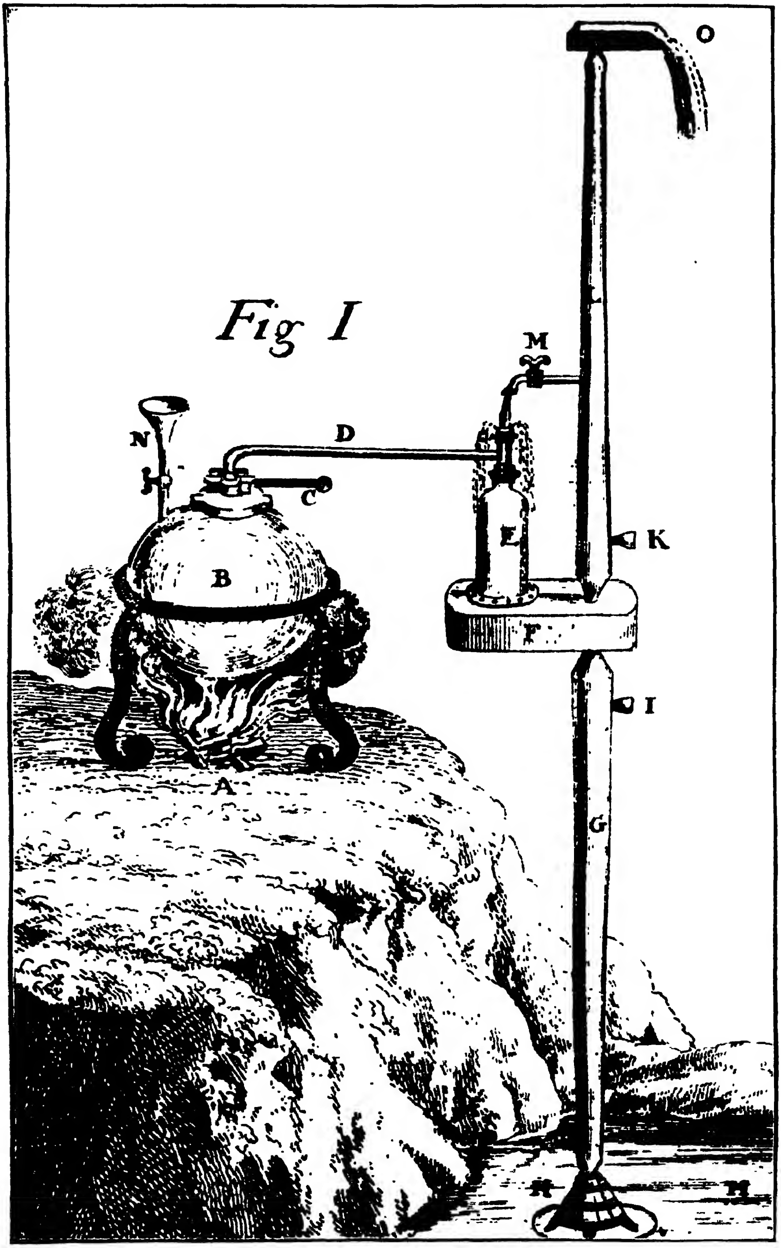
2

The Rising Tide of Invention and Discovery

Experiment and discovery were in the air when in 1663 Worcester published his *Century of Inventions*. The English king, Charles II, toyed with the idea of scientific investigation. A bishop, Dr. Wilkins, had recently written learnedly of mechanical powers and motions. Worcester himself, one of the wealthiest peers of the realm, had not hesitated to devote life and fortune to mechanical pursuits. In 1661 Robert Boyle, son of the Earl of Cork, had published his epoch-making book, *The Sceptical Chymist*. In 1662 the Royal Society was founded, and in 1663—a sure sign of mechanical progress—machinery was first introduced at the Royal Mint. Scientific books were beginning to appear in English about this time, and men were now experimenting more freely with coal for smelting iron, speculating about the strength and elasticity of materials, and seeking more satisfactory explanations for the phenomenon of combustion.

Typical of many who were experimenting in the second half of the 17th century was Denis Papin, a French physician. In 1681 he published an account of his " New Digester for Softening Bones." This contrivance was in effect a boiler constructed to generate steam under pressure for softening meat and bones, and—as he expressed it in his slightly exuberant style—extracting therefrom " marrowy nourishing juices . . . that the most Thrifte housewife declared had been abandoned as but poor prey by ye hungry dogs." The digester was subsequently fitted with a lever safety-valve, of which Papin appears to have been the inventor. Papin also made suggestions for improving the efficiency of furnaces, considered (after Huygens) the possibilities of gunpowder for motive power, and proposed steam as an agent for securing a vacuum to actuate a piston in a cylinder. This last was a variation of an experiment carried out by Otto Guericke some thirty-six years earlier, steam being substituted by Papin for Guericke's air-pump.

In 1698 Thomas Savery, a more successful pioneer, constructed a model of a steam pumping apparatus which he had invented. This he exhibited before William III. at Hampton Court. The idea was patented, and a demonstration of the machine's capabilities was made before the Royal Society in 1699. A description entitled *The Miner's Friend* was published in 1702, notable for the fact that Savery dropped all the mystification hitherto customary in such matters. Savery's invention usually took the form of a boiler for producing steam (with a second smaller boiler for replenishing the first without lowering its temperature) ; two vessels or receivers, oval in section, and an arrangement of pipes, cocks and valves which connected these vessels with the main boiler, and also with the suction and delivery pipes through which water had to be raised from the mine. In operation steam was first admitted to one of these vessels from the boiler, all other connections being shut off. The cock communicating with the water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(Courtesy of the Newcomen Society.)

Savery's steam engine at Kensington as depicted by Bradley, 1718.

suction pipe was then opened, while cold water from a small tank was sprayed over the outside of the vessel. The steam was condensed, lowering the pressure within the vessel, and water immediately rushed up the suction main under pressure of the atmosphere. The suction cock was then closed again, while that connecting with the water delivery pipe was opened. At the same time more steam was admitted from the boiler. This forced the water out through the pipe at the bottom of the vessel, past the open delivery cock, and so up the delivery pipe and away from the pit. A similar sequence of operations was followed with the second vessel, and by filling and emptying the two vessels successively a continuous stream of water was drawn from the mine. A simpler form of this engine, with only one receiver, is shown in the illustration.

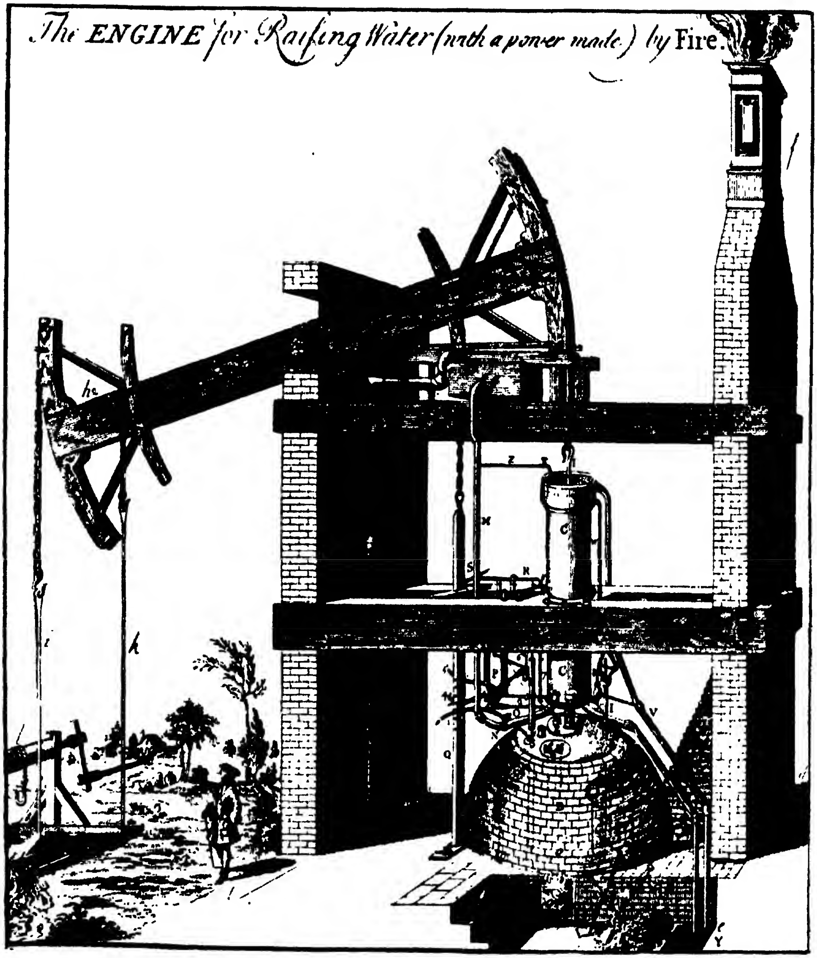
In spite of its ingenuity, and an urgent demand for power, it soon became apparent that the possibilities of this particular invention were very limited. It was exceedingly wasteful in steam consumption ; primarily owing to the alternate heating and cooling of the receivers, and contact between steam and cold water. The engine had to be erected down the pit, or in any case not more than about 26 to 28 feet above the point from which water was drawn ; that is, well within the theoretical limits of atmospheric working. The height to which water could be raised *above* the engine depended, on the other hand, upon steam pressure ; and there was at that time neither knowledge nor skill equal to constructing a boiler capable of withstanding high pressures. Explosions were unpleasantly frequent in consequence. It is not surprising therefore that a development along other lines shortly displaced Savery's " Firework " altogether.

A blacksmith, called Thomas Newcomen, assisted by John Cawley, a plumber and glazier, invented an engine involving use of a piston and cylinder. A model of this was made in 1705 after much experimenting and many failures. In 1712 an opportunity presented itself for developing the invention on a larger scale. An engine was built and applied to the work of pumping water from a colliery in Warwickshire. Many other engines of this type were subsequently installed at collieries and tin mines, and some even found their way to Russia, Sweden, France and Hungary.

In 1753 the first steam-operated engine ever used in America was brought from England by Josiah Hornblower and erected at an old copper mine near Belleville, New Jersey.

In Newcomen's engine a piston moving in a steam cylinder was attached by rod and chain to an overhead oscillating beam. From the other end of the beam depended a rod which passed out of sight down the pit or well to an ordinary pump installed near the water level. A weight on the pump rod tended to keep the piston at the top of its stroke. From a small tank a jacket (or space between the cylinder and an outer casing) could be filled with cold water, and could also be drained by means of a pipe provided for that purpose. Steam, after being admitted to the cylinder from a boiler below, was condensed by filling the cylinder jacket with cold water. This lowered the pressure in the cylinder, which, being open at the top, allowed atmospheric pressure to force the piston down. The pump rod with its weight was thus lifted, operating the pump at the bottom of the pit. Steam was again admitted to the cylinder, and, provision being made for escape of condensed water from the cylinder, as well as condensing water from the cylinder jacket, the piston rose once more and the cycle of operations began again. Subsequently condensing water was injected directly into the cylinder, and the jacket was abolished. Valve gear came later, the cocks and valves being in the beginning turned by hand. It is related that the first engine required three men to operate it. On setting it to work the words were passed : " Snift, Benjy ! " " Blow the fire, Pomery ! " " Work away, Joe ! "

Though an improvement on its predecessor the Newcomen engine was also exceedingly wasteful in fuel. Thus it was that men began to give closer attention to fuel consumption, and many efforts were made to increase not only engine, but also boiler and furnace efficiency. It is not altogether surprising that little progress was made. Oxygen had not yet been discovered, and the " phlogiston " theory of combustion


The ENGINE for Raiſing Water (with a power made) by Fire.
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(Courtesy of the Newcomen Society.)

Newcomen's engine, as delineated by Beighton, 1717.

[To face p. 13.

still held the field. Water was generally regarded as an element, and it was not till 1759 that Black elaborated his views on the subject of latent heat. Writing of efforts then being made to increase boiler efficiency, Stuart remarks: "The smoke flue was made to meander, in every possible way, round the boiler; and it may be that its meanderings were advantageous. . . . There was, however, one fact acknowledged by all—enormous quantities of coals were engulphed in the furnace."[1]

Some very large engines of the Newcomen type were built. The appearance of these primitive power plants is admirably indicated by the accompanying illustration.

It must be conceded that the atmospheric engine devised by Newcomen represents a step forward in the production and application of power. A pumping machine, clumsy and uncouth as any monster of the Mesozoic Age, had been called into being. It embodied much ingenuity but very little science. The world now awaited the advent of a man of genius, able to combine creative faculties with a knowledge of scientific principles, and possessing sufficient imagination to realise the unbounded possibilities of steam. Such a man was James Watt, the story of whose remarkable inventions we now have to tell.

The Outstanding Genius of James Watt

Nothing more clearly indicates the genius of James Watt than the terms of his specification when in 1769 he obtained a patent after six years of experimental work, and four years after the ideas which it covers had occurred to him. As an instrument maker in close touch with Glasgow University, he came to a study of the steam engine already equipped with an extensive knowledge of first principles through reading and association with men of scientific attainments. His friendship with Dr. Black, who about this time had enunciated the principle of latent heat, was in particular of importance in its reactions upon the trend of Watt's investigations. He speedily arrived at the root defect in the invention of his predecessor, namely, the alternate heating and chilling of the cylinder. In other words, he saw efficiency in terms not primarily of coal or steam, but of *heat available for useful work.*

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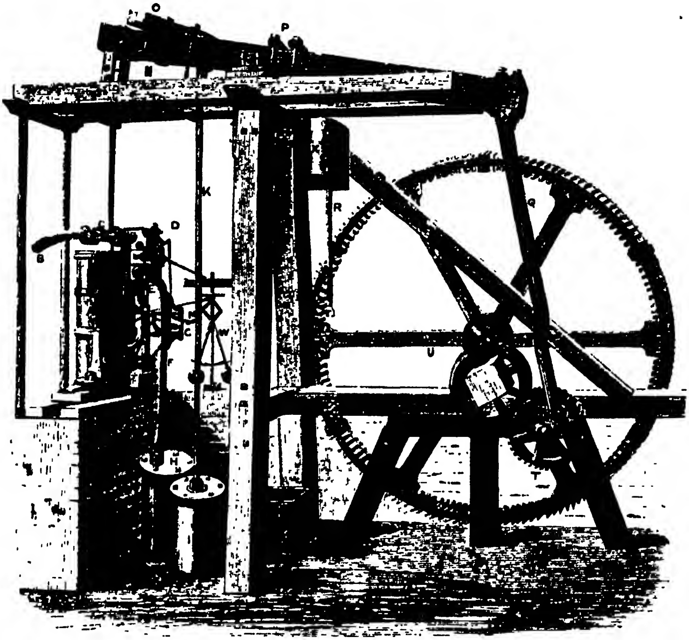
[1] Stuart, *Anecdotes of Steam Engines*. This book, published in 1829, is replete with valuable information relating to the early history of steam.

The remedy for excessive waste of heat he saw must be found in keeping the cylinder as hot as the steam which entered it. How then was the steam to be condensed, since this involved lowering its temperature? The solution of this problem he found in his invention of the condenser. This was a *separate* vessel, kept at as low a temperature as possible, in which the steam was condensed on being released from the cylinder. But steam on being condensed becomes water. This, if allowed to accumulate in the condenser, would render the apparatus ineffective. The pressure within the condenser being now below that of the atmosphere outside, some special means had to be provided to remove this water of condensation. Watt met this difficulty by the use of a small pump, operated by the engine itself. As air leaking into the condenser had also to be withdrawn, so as to maintain the vacuum, the pump undertook both duties. Hence the name "air-pump," by which apparatus performing similar functions is still known.

The methods proposed by Watt for keeping his cylinder hot, apart from discontinuing the practice of discharging cold water over it, were to surround the cylinder with a steam jacket and to enclose it in a case of wood or other material which transmits heat slowly. He further made it clear that he contemplated using the expansive power of steam to move the piston, as well as atmospheric pressure. Where cold water was not available for maintaining the condenser at a low temperature, then the motive force would be supplied by steam at a pressure above that of the atmosphere, and the engine worked without a condenser. He also fitted a cover to the top of the cylinder, which enabled him to apply steam to the upper side of the piston, and maintain the internal temperature. The piston rod was led through a steam-tight device in the cover, known as a stuffing-box.

A year before the patent was taken out Watt entered into partnership with Matthew Boulton, proprietor of the Soho engineering works at Birmingham, and a man of considerable force of character. By 1775 manufacture was begun by the firm of Boulton and Watt, the first engine being ordered by John Wilkinson to work the bellows of his ironworks at Broseley. This engine was completed and set to work in 1776, and extreme care having been taken in its construction and erection, it



Watt's rotative engine. From Smiles's *Lives of Boulton and Watt.* A Steam cylinder. B Steam pipe. C Throttle valve. D Steam valve. E Exhaust valve. F Exhaust pipe. G Valve gearing. H Condenser. I Air pump. K Air pump rod. L Foot valve. M Hand gear tappet rod. N Parallel motion. O Balance weight. P Rocking beam. Q Connecting rod. R Feed pump rod. S Sun wheel. T Planet wheel. U Fly-wheel. W Governor. X Feed water cistern.

proved a great success. The general construction of Watt's engine in its later form is indicated by the accompanying illustration. The air pump discharges the water of condensation into a receptacle known as the "hot-well." From this a supply of hot water is drawn for feeding the boiler, thus increasing the overall efficiency of the plant.

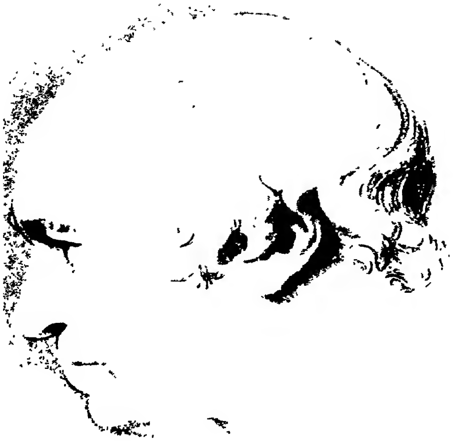
It is fortunate that Watt had more confidence in his engine than in himself. One detail after another was added, improving its efficiency, increasing its power, and widening its scope. Before he retired from active work he was making steam engines which were double acting, vacuum and steam pressure being applied to each side of the piston alternately. Engines were also being constructed to produce rotary motion, and steam was being used expansively. Rotary motion was an enormous advance, opening up as it did countless channels of usefulness. Using steam expansively—that is, cutting off the supply to the cylinder when the piston has only moved through a portion of its stroke, and then allowing the steam already in the cylinder to do work by expansion—led to a further marked economy in fuel.

For much of his life Watt was an invalid, handicapped by a malady which destroyed his self-confidence and periodically robbed him of the capacity to undertake useful work. His recurring fits of despair made life a burden almost too heavy to be borne. Fortunately, his imagination spurred him on to great achievement as well as the magnification of petty worries. The latter are gone and forgotten. The record and results of his work remain, an inspiration and a guide to all those who follow him in the quest for power.

4

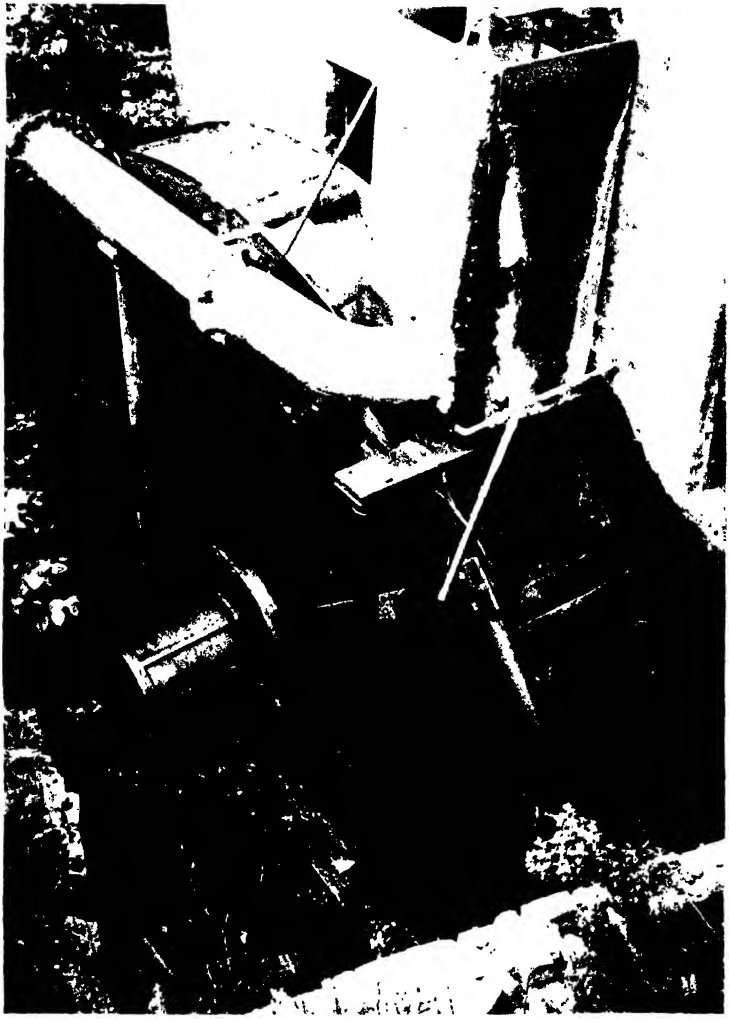
Steam Power dominates Production

The 18th century opened with the invention of Newcomen's engine. At its close Watt's master patent expired. Assuredly no previous century had ever been so pregnant with change, so fraught with momentous consequences for the whole future of mankind.



(*Courtesy of Sir Robert A. Hadfield, Bart.*)

James Watt, 1736–1819.



(*Courtesy of the Newcomen Society.*)

Old water-wheel at Coalbrookdale.

[*To face p.* 137.

It was not alone that man had learned to tap a new and apparently limitless source of power. That, indeed, in its earlier stages was effect rather than cause. While Newcomen and Watt developed their inventions, other men were busily stimulating requirements for power, until at length demand far outran the available supply. For with this century also came far-reaching textile and metallurgical inventions and discoveries. Preceding as they did the application of steam to the production of rotary motion, millowners were clamouring for something on the lines of Watt's rotative engine before he was ready for them. Parallel with these developments a revolution in both inland and ocean transport had been effected. Social and international upheavals and readjustments, and increasing colonial exploitation, had brought English manufacturers in touch with world-wide markets and greatly enlarged resources in raw materials. No wonder they speedily became "steam-mill mad," as Boulton expressed it. Between 1775 and 1800 Watt and his partner erected 289 engines in England, including 84 for cotton mills, 9 for wool and worsted mills, 30 for collieries, 28 for foundries and forges, 22 for copper mines, 18 for canals, and 17 for breweries.

Wind and water were not relegated to the background without a struggle to maintain their ancient pre-eminence. During the 18th century these sources of energy were being used for corn milling, driving sawmills, hammering and rolling metals, and many other industrial purposes. Arkwright's throstle spinning mill was actuated by water power. Smeaton alone erected no less than forty-three water mills, besides numerous windmills. In 1767 we hear of a wind-operated sawmill being erected in the heart of London ; and even as late as 1836 we find some 12,000 windmills, aggregating 6,000 horse-power, still being used in Holland for pumping purposes. But though windmills of the types hitherto used thus lingered on for a time, and indeed still linger on, they were doomed to ultimate extinction by their limitations.[1] The advantages of the new source of power were so manifest that when restrictions on its development passed away with the monopoly of Boulton and Watt, the manufacture of steam engines expanded by leaps and bounds.

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[1] The final blow, so far as the Dutch windmill is concerned, appears to have been given by labour regulations imposed regardless of varying wind conditions.

We shall not deal here with inventions such as those of Henry Maudslay, which made continued progress in the manufacture of all types of machinery, including steam engines, possible. Nor shall we discuss the great steam transport developments of the 19th century—the locomotive, the railway, the iron vessels propelled by steam before which even the " wooden walls " of the British Navy had to give way. It will be enough for our present purpose to note that these developments alone would have sufficed to give steam the dominant position in industry which it was henceforth to occupy as a means of producing power. For not only was steam invaluable for propulsion, it found an ever-widening field of usefulness in the great new industries which the manufacture of locomotives and steamships brought into being.

Since steam power and iron production are so intimately related, some idea of the expansion in the domain ruled over by steam may be gathered from figures showing the increase in output of iron, which took place from about the middle of the 18th century onward. The total quantity of iron made in Great Britain in 1740 is stated to have been 17,000 tons. By 1796 the figure had increased to 124,000 tons, and by 1806 to 250,000 tons. By 1835 the output was 1,000,000 tons, and 2,100,000 tons in 1850. In 1879, rather less than a quarter of a century after Bessemer had invented his process which cheapened the production of steel, the figures had jumped to 5,995,000 tons. Other countries, too, were now producing iron on an extensive scale ; notably the United States, where production was destined before long greatly to surpass even the enormously increased output of Great Britain. Reflected in these figures we catch a glimpse of the far-reaching changes, due largely to the work of James Watt, which had taken place in the production and application of power by the time Charles Parsons was developing the first practicable steam turbine, an invention which in its turn has largely replaced the reciprocating steam engine, and, in conjunction with the electric generator and motor, threatens now to drive it out of the industrial field altogether.

The changes wrought in methods and scope of production were indeed stupendous. The contrast must have been particularly impressive during the period when wind and water were still being widely utilised in spite of the rapid rise of the steam engine. Here is a picture of primitive conditions still existing early in the 19th century.

> " One if not two of the tower windmills above the steps at the top of Clayton Street, Liverpool, was worked in the early twenties by Richard Rawsthorne. . . . My father had not then commenced milling, and kept a bread and flour shop in Gerard Street close by. It was summer time, and there had been neither rain nor wind for weeks. The country watermills at Kirkby, Aintree and Sefton had long been dry. My father had wheat at White's windmill, Crabtree Lane, Jerry Shaw's North Shore windmill, and Rawsthorne's at Clayton Street, but could get no flour ; neither could anyone else, and they were almost stranded. One Saturday night, or rather Sunday morning, my father after a long day had gone to rest, when a fresh wind sprang up. Tired as he was he hurried off at once to Rawsthorne's mill, not many yards away, intent on persuading old Richard to start his mill if possible. There were penalties for running a mill on Sunday, but these had to be risked. . . ." [1]

Limitations such as these, with their accompanying burden of anxiety, had to be faced not only in the production of flour before the coming of steam, but throughout industry where wind and water power were used. Though there is much make-believe about the " idyllic " conditions of the old wind and water-mill days, the plain truth is that life must then have been far more arduous, and have had far fewer amenities than now. Whereas grain and flour are now handled automatically by power-driven machinery, they were in the good old days almost entirely carried up and down the mill by the miller and his men, making an enormous demand on their bodily strength. Looking back beyond the age of steam-driven machinery we see a world in which heavy bodily toil was still accepted as the common lot; in which, even for unremitting drudgery, the return was pitifully meagre. John Stuart Mill questioned whether machinery had lightened the toil of a single human being. But Mill lived too close to the mechanical revolution to see it in its true perspective. Even now we only begin to see what was really happening. Men were caught up in a mighty swirl of production which swept them from their moorings, obliterated ancient landmarks and destroyed the scale of values to which they had hitherto been accustomed. Under such circumstances it was inevitable that the new era should at first be accompanied by glaring evils. For these evils neither steam nor machinery can be held accountable. The tendency of power-driven machinery has always been towards a reduction of bodily toil, making possible also an incomparably greater output in proportion to expenditure of human energy. With economic adjustment, it can only be a matter of time before the unintelligent human drudge, the basis of all previous civilisations, becomes a thing of the past. There has, indeed, been too ready a disposition to look only at the darker aspects of the dominance of steam; to think fearfully of men being concentrated in murky towns overshadowed by towering chimneys, toiling in iron and steel works, outlined gauntly at night against the lurid glare of furnaces, deafened by the ceaseless din of cyclopean hammers, spending the greater part of their lives in the gloomy environment provided by foundry, forge, and mine and mill. We propose in this work to emphasise our conviction that these features are for the most part transient, and are in any case far less significant than the opportunities which power-operated machinery offers for superseding toil almost without limit.

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[1] *History of Corn Milling*, Bennett and Elton, Vol. II, p. 317.

5

Steam Raising Plant

Having traced the earlier phases of the Steam Age, we now come to more recent and far more significant and interesting developments. As these must be considered in some detail, it will be expedient to tell here of how steam is produced, leaving its utilisation in engines and turbines to be dealt with later.

Steam-raising plant has two quite distinct functions. Arrangements have first to be made for the proper combustion of fuel, which involves extracting the greatest possible amount of heat from every pound of coal, or whatever it may be that is burned in the furnace. This heat has then to be transferred to water in the boiler proper, the water being evaporated into steam in the process. Both these functions must be fulfilled with a minimum amount of danger. Imprisoned steam behaves very like an explosive. Professor Thurston has calculated that a cubic foot of heated water under a pressure of 60 pounds [1] has about the same energy as 1 pound of gunpowder, and that there is sufficient energy stored in a plain cylinder boiler containing steam at 100 pounds pressure to project it to a height of over three and a half miles. It is scarcely surprising therefore that little progress in boiler design was made for many decades. Watt, as we have noted, was always careful to use low pressure steam. In more heroic and adventurous spirit Trevithick used steam at 60 pounds pressure as early as 1801 on his Cambourne road locomotive. Steam pressures of this order were also used in America at an early date. But for the greater part of a century many engineers continued to construct boilers—and are to-day still constructing boilers—very similar to Trevithick's, except that they are larger, and are better able to withstand the disruptive energy of steam. With such boilers—the shell or fire-tube type—we shall not be concerned here, beyond pointing out that they may be horizontal or vertical, are usually fitted with one, two or more flues, while the products of combustion may also be taken through a number of tubes in order to bring the heat into more intimate contact with the water. One and all will eventually disappear from the industrial field with the increasing generation and use of electricity, though here and there they may linger on, like old-type windmills and water-wheels, long after their day is done.

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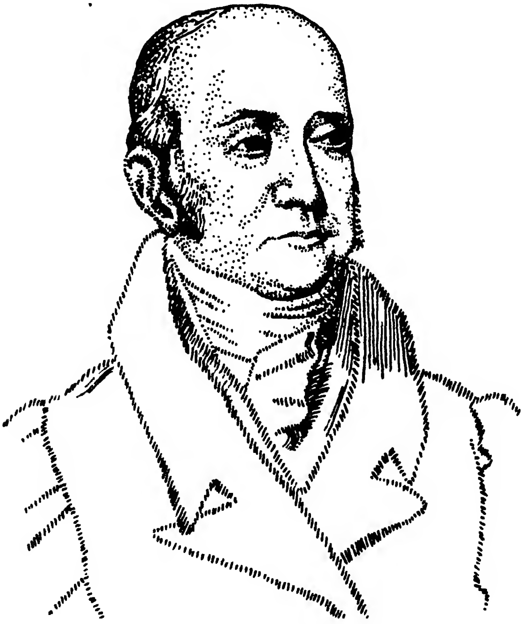
[1] " A pressure of 60 pounds " is used here as shorthand for " a pressure of 60 pounds to the square inch above atmospheric pressure."

The water-tube boiler is the only type adopted now in modern large-scale steam-raising plants. One of the earliest British water-tube boilers was probably that constructed for his steam carriage by Sir Goldsworthy Gurney in 1825, but it was not until the American engineer, Perkins, in 1831 devised a simple and ingenious way of improving circulation in boilers that the first step towards ultimate adoption of scientific principles was taken.[1] But we will return to boiler circulation presently. Let us consider first the combustion of fuel, the evolution of heat, and its transfer to the water, resulting in evaporation and the generation of steam.



Jacob Perkins, 1766–1849. From an old engraving.

Combustion has been defined as the union of two dissimilar substances evolving heat and light. So far as ordinary steam-raising practice is concerned, one of these substances is oxygen and the other is the fuel used. Fuel requires air—not too little, not too much—for its complete combustion. No boiler utilises all the heat evolved. Some of it is conveyed up the chimney in the waste gases, some is dissipated by radiation from the sides of the furnace. In general, it is found that the losses by radiation are, roughly speaking, inversely proportional to the rate of combustion. Thus for any given type of fuel, the more rapidly it is burned the greater is the efficiency obtained. In some respects a boiler is very like a living organism. Both consume carbon and oxygen, and for both this food must be supplied in suitable proportions. So also may it be said that the amount of work each can do depends, within individual limitations, upon the quality and quantity of food supplied ; starvation resulting from too little of the right kind, indigestion or derangement following upon excess. Finally, pure water, good circulation, good clothing, cleanliness and general care are essential for each if illness and inefficiency are to be avoided.

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[1] Perkins was the first to experiment with ultra high pressure steam, having reached a pressure of 1,400 pounds in 1827.

Let us now assume that as much of the heat of combustion as possible is transferred to the water. The water evaporates into steam, and in the process most of the heat vanishes. What has become of it ?

If we heat a quantity of water in an ordinary open vessel to boiling point (212° F.) we shall find that, however much more heat we apply, the water will not get any hotter. Instead it begins to turn into steam. Not until we have added enough heat to have raised the temperature of the water (had this been possible) to 1,178° F. will it have all become steam. Nevertheless, this steam will still be at the temperature of 212° F. at which we began. We find that over four-fifths of our heat has been stored up in the steam—become " latent," as we call it. This is supported by the fact that the energy is not lost, but reappears again when the process is reversed.

Now this capacity of water to store up heat when converted into steam must be utilised to the utmost. But a difficulty arises from the fact that water is a poor conductor of heat, so that the water nearest the fire cannot pass its heat on to the upper layers by direct contact.

When heating water to 212° F. in an open vessel it will be noticed that currents and eddies are formed. The heated water at the bottom expands, and, weighing less now for a given bulk, it rises to the top, the colder water then descending. The latter becomes heated in its turn and so the water moves continually up and down. If under these circumstances still more heat is added, the upward currents interfere to such an extent with those passing downwards that the steam foams up with water particles in suspension, and " the pot boils over." But in steam-raising plant wet steam must be avoided. What is required at the engine or turbine is steam, not hot water. By adopting the ingenious idea of Perkins already mentioned, much of this trouble can be overcome. A second and smaller vessel is fitted inside the larger one, leaving a space between the two. In the bottom of the inner vessel is a hole. Since there is most heat all round the outside of the outer vessel, the water rises in the space between the inner and outer walls. The colder water then descends through the hole in the bottom of the inner vessel. The up and down currents are thus largely separated, so that even when steam is generated at a much greater rate by forcing the fire, the vessel no longer foams or boils over.

It will be seen at once that this is an invention of cardinal importance. We have already referred to the desirability for rapid combustion. With this arrangement we can speed up combustion without raising an undue proportion of wet steam. But that is not all. Better circulation means that the whole of the water is heated more quickly and effectively. This implies greater efficiency, and in addition makes for greater durability of the plant and reduces the risk of explosions. For an even temperature is distributed throughout ; and nothing causes more wear and tear in a boiler or is a more fertile cause of explosions than inequalities of temperature with correspondingly unequal expansion and contraction.

But so far we have only considered the most elementary stage in the evolution of the modern water-tube boiler. A further improvement on the simple expedient of Perkins may be secured by the adoption of a boiler constructed like a

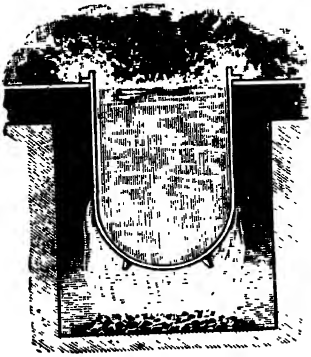


Fig. 1.

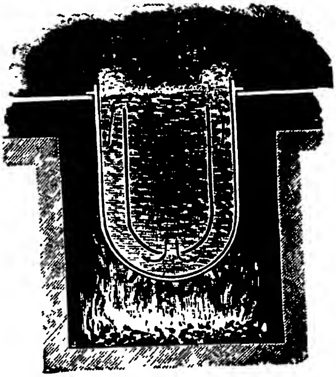


Fig. 2.

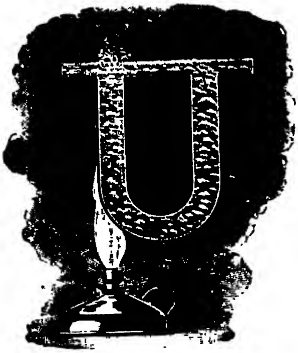
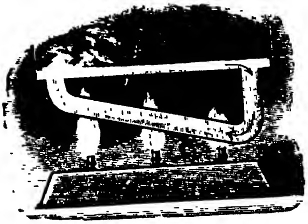


Fig. 3.



(Courtesy of Messrs. Babcock and Wilcox, Ld.

Fig. 4.

Diagrams illustrating trend of water-tube boiler evolution.

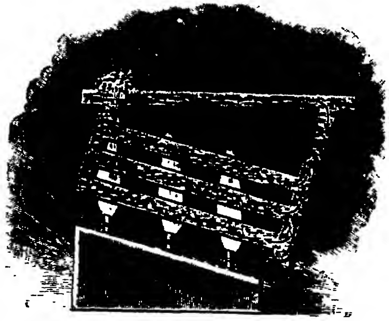
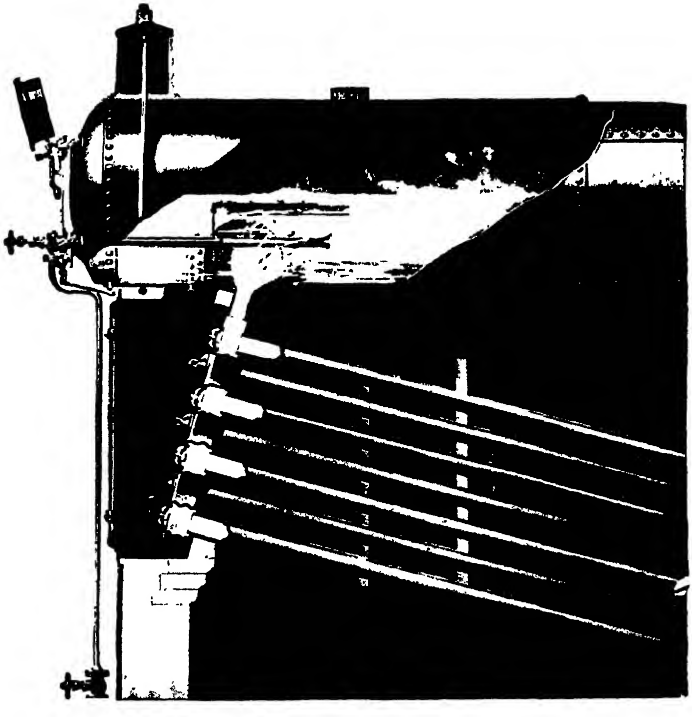


Fig. 5.



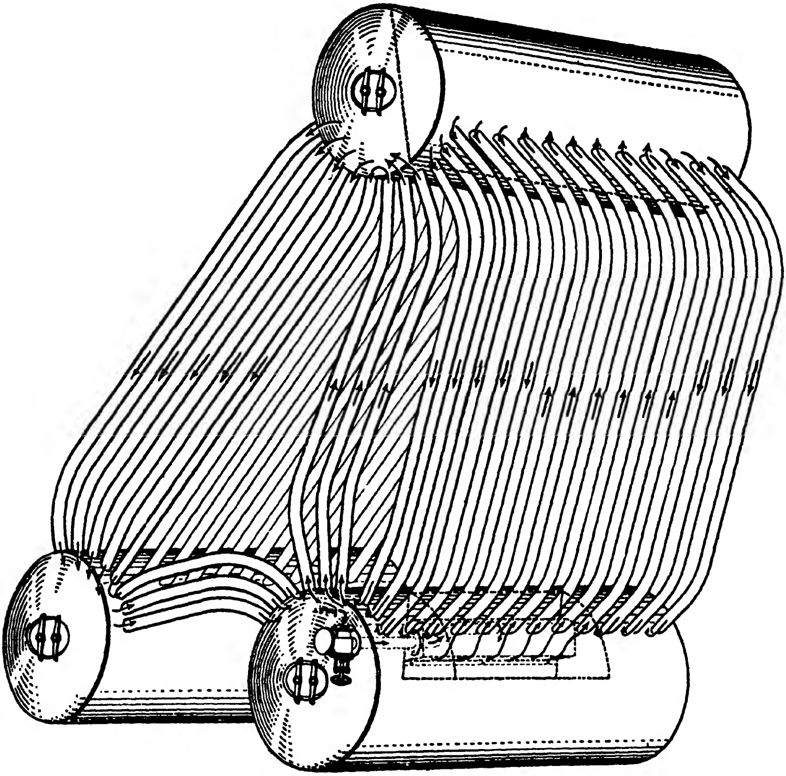
(*Courtesy of Messrs. Babcock and Wilcox, Ltd.*)

Fig. 6.

Diagrams illustrating trend of water-tube boiler evolution.

[*To face p.* 145.

U-tube depending from a horizontal vessel of water. Upon heat being applied to one leg of the U-tube a circulation is set up in which all possibility of interference between up and down currents is eliminated. Again, the leg which is heated can be inclined so as to present more surface to the source of heat ; and by dividing this inclined portion into a number of separate tubes, still more heating surface and therefore higher efficiency is obtained. So at last the form of the modern water-tube boiler begins clearly to emerge. There are many detailed variations in actual practice, but however the designs

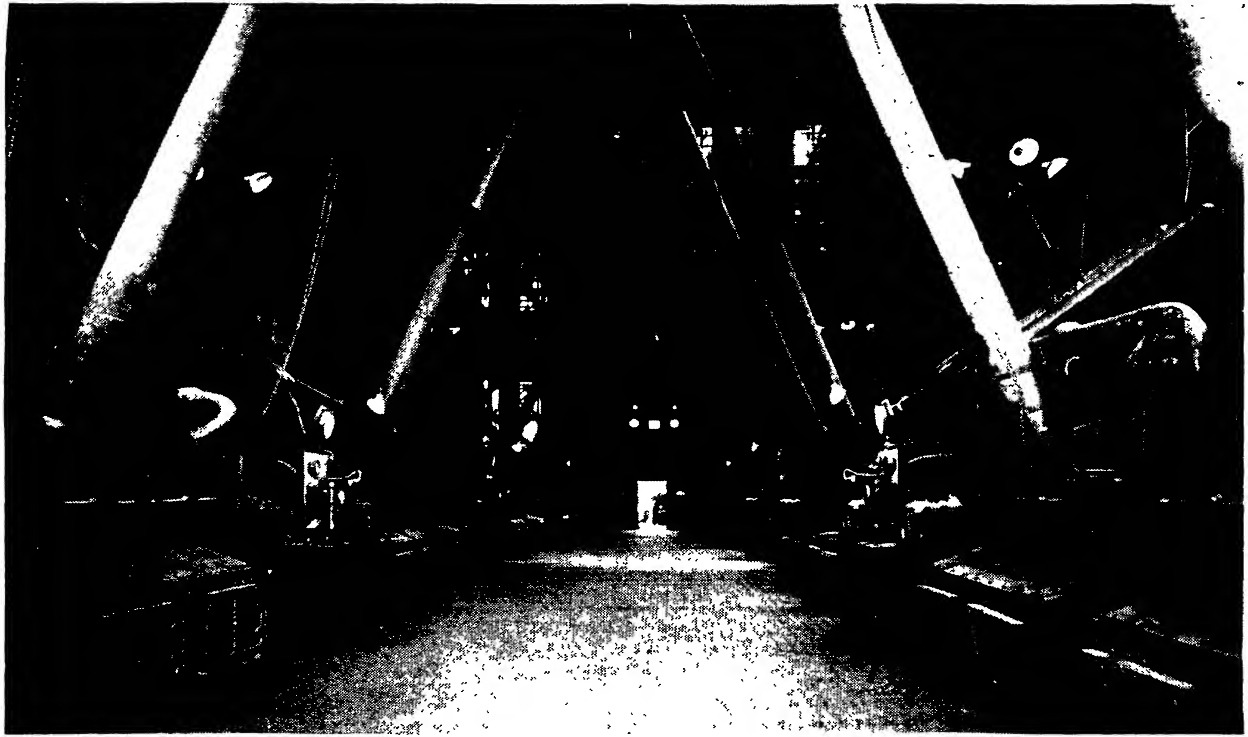


Circulation diagram of a Stirling tri-drum water-tube boiler.

of manufacturers may vary, the principle of efficient circulation underlies them all.

Modern steam-raising plant incorporates science to a remarkable degree. We cannot even enumerate here the many auxiliary devices now added to the boiler house to increase efficiency. All materials used, steam produced, pressures, temperatures and so forth are automatically weighed, measured, indicated, or recorded as the case may be. What is perhaps even more noticeable is the extent to which body and soul destroying drudgery has been abolished. Gone are the rows of grimy stokers, wiping sweaty hands and faces on cotton waste in the intervals of shovelling coal. Gone also are the numerous drudges, who used to be seen lurking about in the shadows when not wheeling barrowloads of coal or ashes ; or emerging from hot flues, eyes and throats inflamed and irritated with dust, after clearing away the accumulated flue-dust ; or, again, it may be clambering precariously—and painfully—over hot uncovered steam pipes and suchlike unpleasant obstacles on top of the boilers. Though the output of steam is now vastly greater, the boiler house at any modern power station strikes the visitor as being almost deserted. Here and there a man may be seen standing by, watching a gauge, studying a chart, seeing that this or that part of the automatic mechanism is functioning satisfactorily. But that is all.

In many power stations coal is now pulverised and then pumped in powdered form through pipes to the furnaces, where it burns in a long flame like so much gas. Otherwise, coal is taken from the store outside by elevators and conveyors, and delivered to the furnaces by automatic stoking machinery, or, alternatively, falls on to a grate constructed like an endless chain. As this chain-grate moves slowly forward over sprockets the coal gradually approaches the hottest part of the combustion chamber and is consumed ; while the ashes and clinker travel on, to fall off at the back of the chamber on to other conveyors and so away. Boiler-flue dust is sucked up by a kind of gigantic vacuum cleaner. There is no need to go into the flues now so far as accumulations of dust are concerned.



(*Courtesy of Messrs. Babcock and Wilcox, Ltd.*)

Interior of a modern boiler house, North Tees Power Station B.

[*To face p.* :

The vacuum pump is set going and valves on the dust mains are opened. The machinery does the rest.[1]

The tendency in steam raising practice is all in the direction of high pressures and temperatures. It is now universal practice to equip water-tube boilers with superheaters, consisting of additional tubes through which the steam passes before being taken to an engine or turbine. The tubes are heated and the steam is raised to a higher temperature than the water from which it was evaporated. In this way greatly increased economy is secured. Moisture cannot exist in the presence of superheated steam. Whatever tendency there may be for the steam to condense is overcome by the extra heat units added during its passage through the superheater.

Metallurgical research has produced metals suitable for use at 900° F. steam temperature, while boilers have been constructed to operate satisfactorily at over 1,400 lbs. pressure. How far ultra-high pressures and temperatures will become general is a subject on which we may more conveniently enlarge after discussing other aspects of modern steam power plant.[2]

Modern Reciprocating Steam Engines

In recent years the reciprocating steam engine has developed along many divergent lines. Each type has its special features of interest. Each bears ample evidence, in its design and construction, of applied science, years of patient planning and scheming, the ceaseless quest for efficiency and simplification, and a delicate accuracy of workmanship unknown to any previous generation. Nevertheless, few present entirely new features. Most differ from Watt's engine more in refinement of detail than in principle. We shall therefore confine our attention here to the high-speed, enclosed steam engine, which embodies more novel, important, and interesting departures from precedent than any other type.

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[1] This process has been largely developed by H. Cecil Booth, M.I.C.E., the original inventor and patentee of the vacuum cleaner.

[2] It is of historical interest to record here that the Romans appear to have made use of some form of water-tube boiler for heating water for baths. Thus Seneca, writing in the 1st century A.D. (*Questiones Naturales*, Book III, Chapter XXIV), remarks : " We are in the habit of constructing worms, and cylinders, and vessels of several other designs in which thin copper pipes are laid in descending spiral coils. The object is to make the water meet the same fire over and over again, and flow through a space sufficient for heating it up ; so, entering as cold, it comes out hot."—Clarke's translation.

The modern high-speed engine came into being between 1870 and 1890. Despite undoubted progress a large number of engines made prior to that period were, according to modern standards, very crude pieces of ironmongery indeed. The new facilities provided by Henry Maudslay and Joseph Whitworth for accurate workmanship were not widely utilised. The slow-running engines of those times would jog along almost indefinitely provided the parts were made strong enough ; and the makers themselves (with few exceptions, like George H. Corliss in America) were content to jog along on the good old lines, leaving experiment and new-fangled ideas severely alone. Decades passed with very little marked change. But by 1870 a new method of securing economy was attracting attention and gaining adherents on both sides of the Atlantic. Writing in 1871, R. H. Thurston draws attention to the fact that : " High speed and short strokes are essential elements of economy. It is now well understood that all the surfaces with which the steam comes in contact condense it. Obviously one way to diminish this loss is to reduce the extent of surface to which the steam is exposed." And a year later another American, Charles T. Porter of Philadelphia, remarked that " all builders now aim generally to run their engines as fast as they consider to be prudent, each one, however, disapproving very strongly of speeds above that to which he finds himself limited." British engineers, too, were giving this matter their consideration. Peter Brotherhood began, in 1872, to develop a novel type of high-speed engine, and in 1873 P. W. Willans turned his attention to the possibilities of high speeds, eventually constructing an engine which became one of the finest of its type in the world—only to be replaced later by a still more successful development.

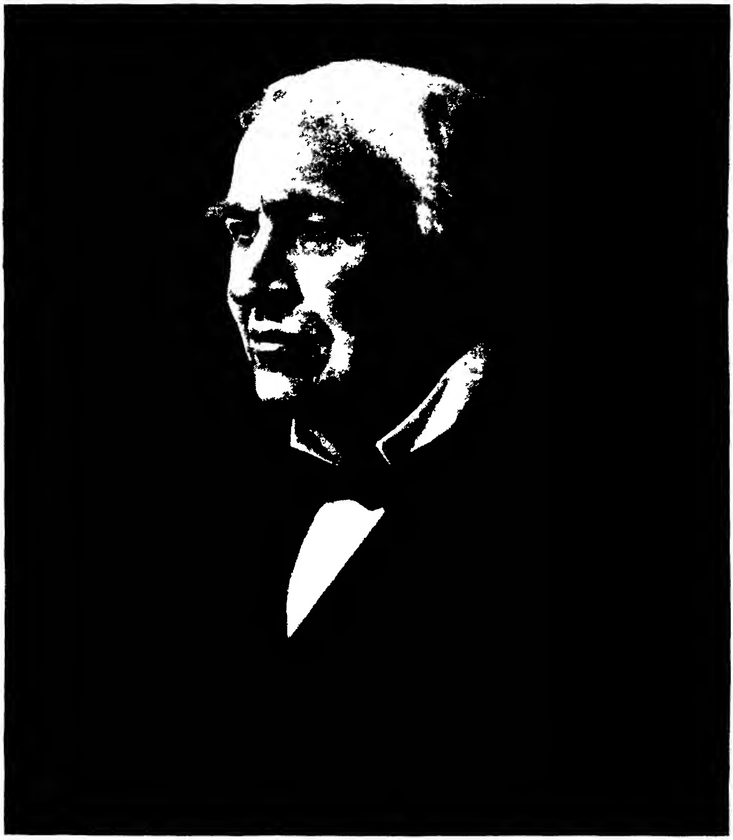
To use a little steam at a time, to use it quickly and to keep it hot and thus lose as little of its energy as possible, is the basic principle of the quick-revolution engine which was thus struggling into being. A greater number of revolutions a minute does not necessarily mean a greater linear speed for the piston ; nevertheless, it will be seen that a high piston speed combined with a short stroke gives the steam the least opportunity to part with its heat—that is, its energy—to the cylinder walls. But a short stroke and a high speed of revolution introduces new difficulties. Thus, in order to lubricate engine bearings it is essential that there should be some clearance, however small, between the bearings and the pins, or shafts, rotating in them. If under these circumstances the forces in the engine are suddenly reversed, as at the end of the stroke, there is bound to be a shock unless special precautions are taken ; producing a knock which rapidly becomes worse as the bearings wear away. Again, in the old days vibration due to reciprocating masses was not nearly so great a problem as in a high-speed engine. The forces setting up vibration are quadrupled when speed is doubled. Willans in England and Westinghouse in America successfully met these difficulties by adopting a single-acting engine. With plenty of cushioning at the end of the stroke (obtained partly by compressing imprisoned steam in the cylinder) it was possible to ensure that a push or thrust was always exerted on the piston, no matter what the position of the moving parts. This greatly reduced the wear on the bearings. It was also easier to balance a single-acting engine, and so vibration even at high speeds was more readily eliminated.

Both English and American pioneers shut the moving parts up in a cast-iron box or crank-chamber, and filling this partly with oil, relied upon splashing to lubricate the bearings. The cast-iron box at first aroused much opposition, particularly when engines of this type were put into the care of marine engineers. " It was considered to be tempting Providence," said Willans, " to fit any engine in a ship unless the attendants could see the connecting rods and get splashed with oil from them ; notwithstanding the fact that in the matter of pistons and valves people were happy to infer their presence from the results." However, opposition died down. The single-acting enclosed engine proved such a success that after a time most engineers thought " constant thrust " was essential for the satisfactory operation of high-speed engines over any prolonged period.

Between 1878 and 1880 Edison in America and Swan in England devised a practicable electric incandescent lamp. Neither Swan nor Edison " invented " the incandescent electric lamp, though the work of both was of cardinal importance in ensuring its ultimate success. Working independently, both achieved notable results at about the same time. Contributory to the perfection of the incandescent lamp were the invention of the Sprengel air pump in 1864, and numerous experiments made with the object of producing artificial silk. Swan's early lamp filaments were made from cotton thread parchmentised by sulphuric acid, but he subsequently invented an artificial silk filament made by ejecting collodion (a gluey solution of gun-cotton in alcohol and ether) into a suitable coagulating medium. The new filament was exhibited in London in 1884, and, on being denitrated and carbonised, was extensively used in the manufacture of electric lamps.

In 1879 Edison had produced, in his laboratory at Menlo Park, N.J., an incandescent lamp with a filament of carbonised cotton sewing thread sealed in a glass globe exhausted of air, which burned for forty hours. A number of lamps were made on this basis, and used to illuminate some houses and streets in Menlo Park, and over 3,000 people went out from New York on the last night of 1879 to see the new development. The Edison Electric Light Co. was incorporated early in 1880 ; and in 1882 the Pearl Street Station, New York—the first central power station in the world for generating and distributing electricity to public consumers—was started up. The plant consisted of Edison dynamos direct-coupled to Porter-Allen engines, steam being generated by Babcock and Wilcox water-tube boilers.

Meanwhile Crompton, Ferranti, and others were forging ahead in England, and a great boom in electric lighting followed. Here was a wonderful opportunity for the high-speed engine to show what it could do. Dynamos being



Thos A Edison

To Hugh P. Vowles —

Thomas Alva Edison.

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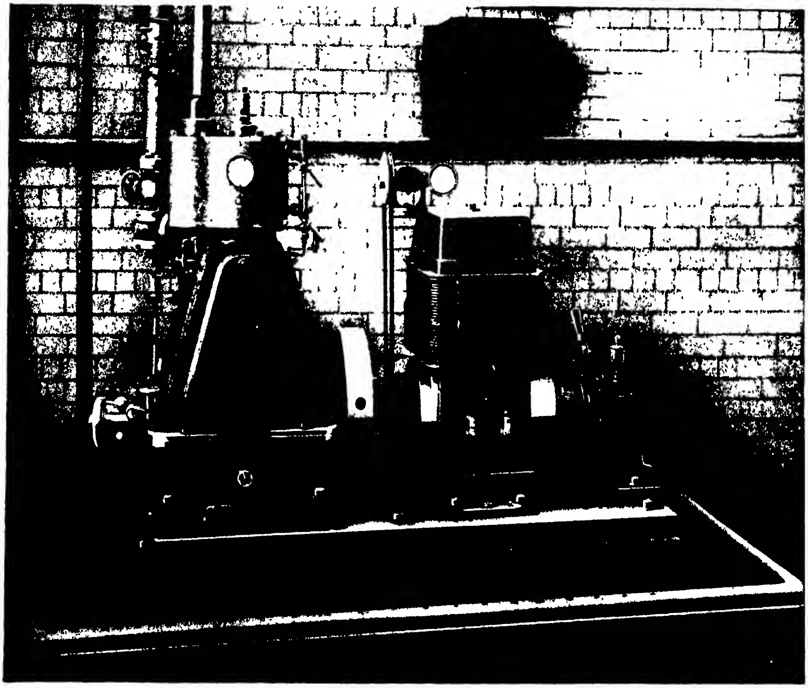

(Courtesy of Messrs. Belliss and Morcom, Ltd.,

The first high-speed forced lubrication steam engine, 1890.

[To face p. 151.

high-speed machines, most pioneers attempted to couple engines direct to dynamo armatures. Up to that time electric lighting—what there was of it—had been entirely dependent upon the arc lamp. Regularity of speed was of little moment, since arc lamps spat and flickered horribly anyhow. But for the incandescent lamp regularity of running became an urgent necessity. A surge in speed, and whole batches of lamps would be burnt out. The high-speed engine was found wanting in this regard. So for a time dynamos continued to be driven through belting; fluctuations being partly absorbed by a slack belt, which on this account was highly esteemed in many quarters. Those were the days when the dominating noise in a power house was the angry whack, whack, whack, of the belt on the dynamo pulley. Meanwhile a great effort was made to improve engine speed regulation, with the result that a sensitive governor was eventually evolved which kept the speed of the engine steady within very fine limits indeed. Direct coupling came into vogue, the wholesale burning out of lamps ceased, lights no longer fluttered so frequently between an uncanny brightness and a dull, resentful red, and the modern era of electric lighting set in.

But the Willans and Westinghouse type engines were doomed. There was one engineer at least who had no faith in the "constant thrust" principle. This was A. C. Pain, who in 1890 conceived the idea of forcing oil into all bearings by means of a pump. A film of oil under pressure would then separate these bearings from the parts working in them. The high speed, enclosed, *double-acting*, *forced lubrication* engine, first developed by Belliss and Morcom, was the result. It immediately proved to be a great success. Here was an engine in which shock and wear were reduced to reasonable working limits; and being double acting it occupied much less space than its single acting, splash lubrication competitors. The principle has since come into universal use and is now applied to high-speed engines of almost every variety, whether actuated by steam or not.

The progress thus made in about twenty years—most of it in little more than ten—was phenomenal. It was largely due to rapidly increasing application of science to practice, and to an influx of brilliant and flexible-minded young men into the new electrical industry. But even as late as 1885 power engineering still retained many features which remind one of "Alice in Wonderland." Turning to the records of the leading British engineering institutions, we find Crompton, in 1885, greatly admiring the Willans engine because it was possible to come "within 5 or 6 feet of it without being splashed with oil"; and referring to a number of engines recently under his control, the bearings of which were open as much as $\frac{3}{8}$ths inch after a long run. We find John I. Thornycroft also admiring the Willans engine because "apparently everything was turned up in the lathe." And turning to other sources of information we read of one early electric supply undertaking not far from London being started up in a hay-loft. This was considered convenient because in daylight, when the load went off, the engine came in useful for driving the chaff-cutter! And in 1886 or a little later the lighting plant at Fifth Avenue Hotel, Broadway, New York, was equipped with a kind of basket over the bearings in which blocks of ice were placed to keep the bearings cool.[1]

Contrast this sort of thing with modern conditions. Forced lubrication high-speed engines of to-day will run steadily under the most arduous conditions of load, week after week and month after month; without a hot bearing, without a hitch, without even a stop, and with practically no visible signs of wear except over a period of years. Such engines are indeed a marvellous example of what can be done by the application of science to design, materials and workmanship. Nevertheless, even as they replaced their predecessors, they are themselves now being largely replaced by even more wonderful developments still. To some of these later developments we will now turn.

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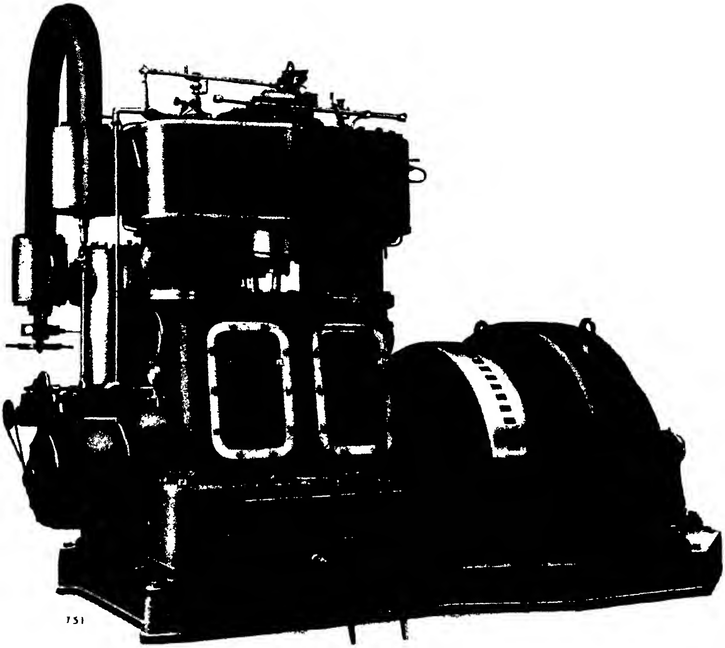
[1] See "Early Days of the Electrical Industry,"—*Electrical Times*, 1921-22.



(*Courtesy of Messrs. Belliss and Morcom, Ltd.*)

A modern high-speed steam engine.

CHAPTER II

THE TRIUMPH OF THE STEAM TURBINE

I

Invention and Early Evolution

WHILE the reciprocating steam engine was revolutionising industry and transport, certain inventors sought to produce rotary motion by direct application of steam to a wheel. Some hoped to dispense with connecting rods, cross-heads and cranks, whilst still retaining a measure of reciprocating motion. Others endeavoured to improve upon Heron's very inefficient " whirling eolipile "—inefficient because only a small fraction of the energy in the steam was utilised effectively in producing rotary motion. Practical men were inclined to deprecate the efforts of these inventors. It is on record that one experimentalist was curtly informed by a past president of the Institution of Civil Engineers that natural movements such as walking, flying and swimming are reciprocatory ; and that though it may be convenient to apply power by rotation, it is on the whole better to obtain power by reciprocation. But inventors are a hopeful race ; and it was not so much lack of vision in " practical " men, as practical difficulties that delayed the invention of the steam turbine until long after substantial progress with water turbines had been made. Steam is much less tractable than water. One of its peculiarities is that when allowed to escape from a boiler under pressure it issues at a very high velocity. At 200 lbs. pressure, for example, steam will discharge into the atmosphere with a velocity of over 3,000 feet a second. If the steam is superheated by 100° F. this velocity is raised to about 3,250 feet a second, and this again will be increased to over 4,000 feet a second if the discharge takes place into a vacuum—which is what happens when admitted to a turbine exhausting into a condenser.

Now the only steam turbine that most early inventors could visualise was one in which a single wheel was pushed round by a jet of steam. But when energy is extracted by letting steam impinge on buckets or blades fixed to the rim of a single wheel, it is necessary for efficient working that the velocity of the blades should be nearly one-half the velocity of the steam.[1] This, with steam at 200 lbs. pressure, would mean a wheel the rim of which travelled at somewhere about 2,000 feet a second ; or, say, about 1,360 miles an hour. Such a speed was of course hopelessly beyond the limitations imposed by lack of metallurgical science and constructional facilities during the 18th and 19th centuries. Even now it is impracticable, and is, moreover, very undesirable.

In spite of difficulties, or perhaps because they did not clearly realise what they had to contend with, inventors continued to probe into the possibilities of a steam-rotated wheel. De Kempelen (1784), Bresson (1852), Heel (1852), Harthan (1858) and Perrigault (1865) are a few of those who grappled unsuccessfully with the problem of developing Heron's eolipile into an engine capable of doing useful work. Of these Harthan was the first to point to a more satisfactory way of utilising the energy of steam directly in the production of rotary motion. But it was not until 1884 that the first steam turbine capable of practical development was invented by the Hon. Charles Parsons, son of the Earl of Rosse. His first machine was exhibited in 1885, and consisted of a cylindrical casing enclosing a rotating shaft. The essential feature of this turbine lay in the fact that in effect it combined a number of wheels mounted on one shaft ; wheels and shaft together comprising what is now called a " rotor." To the advantages of this arrangement we shall return later. In the original machine the rim of each wheel was slotted so as to leave a number of flat projecting " blades " set obliquely to the plane of the wheel. Steam travelling in the direction of the axis of the rotor would part with some of its energy to the blades, causing the rotor to revolve. The steam was not allowed to travel in a straight line, however. Rows of

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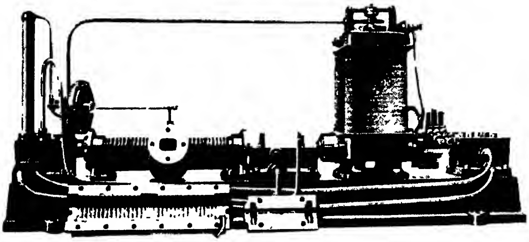
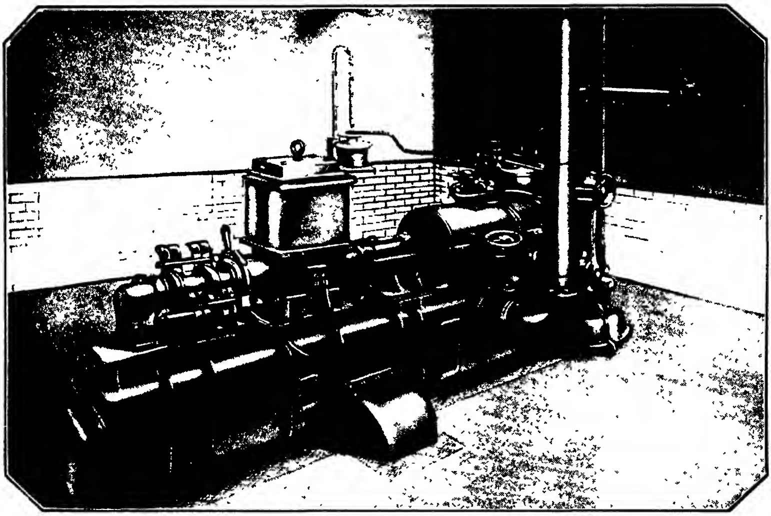
[1] So also with water turbines. See explanation in Book II, Chapter IV, Section 2.



Parsons' original steam turbine, 1884. Output of the dynamo, 5 electrical horse-power.



(Courtesy of Messrs. C. A. Parsons & Co., Ltd.)

Early Parsons steam turbine of 1896. Self-contained with dynamo, condenser, and pumps above floor-level.

2

Steam Turbines of To-day

The endeavour to simplify has led some writers to discuss the steam turbine as though it was merely a novel kind of windmill. But this is to miss its most significant and interesting aspects. A steam turbine is primarily a heat engine, and its action should always be thought of in terms of heat. The leading principles of turbine design can be easily followed; they must be followed by anyone who desires to understand how a steam turbine really works; and to such principles we shall turn the reader's attention without further delay.

In the first place we cannot too frequently remind ourselves that even in theory we can get no more energy out of steam than we put into it. In practice we get less. We put energy into steam in the form of heat. We take it out again—in various ways. Because of its internal energy, imparted to it in the form of heat, steam exerts a pressure on the vessel which contains it. This pressure can, as we have seen, be applied to a piston moving in a cylinder. And once a quantity of steam has been admitted to the cylinder, it can be allowed to expand under its internal energy and so carry the piston forward for the remainder of the stroke. If the steam still contains available energy, then it can be conveyed to another and larger cylinder where it may expand further and do more work. This is one way of taking energy out of steam. It is not the method adopted in a turbine, however, and here we come to the essential difference between the action of a steam turbine and that of a reciprocating engine. In the former the heat energy of steam is not directly used to set the mechanism in motion. *It is first used to set the steam itself in motion.* The heat energy is thus converted into kinetic or " going " energy, and this in turn is made to do work on the turbine blades.

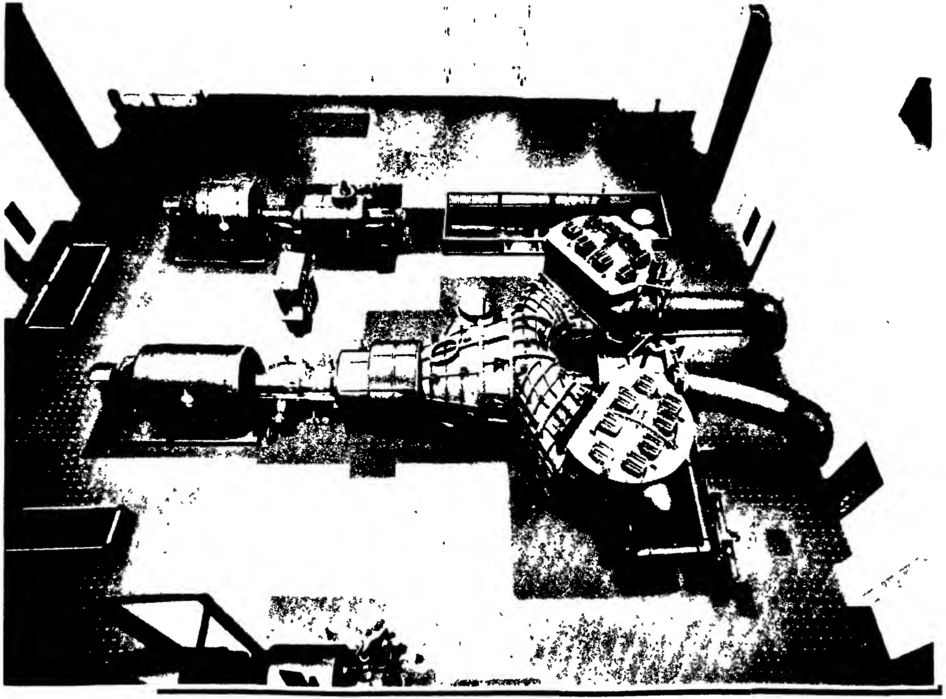
Let us at this stage consider the behaviour of steam when passing through a pipe or channel from a region of high pressure to one where the pressure is less. We find that the steam increases in volume and acquires velocity. In practice some energy is lost in the process. Heat passes away to the surrounding surfaces, friction accounts for further loss, energy is frittered away in forming eddies in the steam. This is precisely what happens in the pipes or nozzles by which steam enters a turbine. But under ideal conditions the total heat energy lost by the steam would be equal to the total gain in kinetic energy. Turbine designers continually endeavour to reduce losses to a minimum and so approach ideal conditions as nearly as possible. Just as a thrifty man endeavours to spend his money to advantage, and in any case to account for all he receives, doing his best to eliminate what Stevenson called " spontaneous lapse of coin," so steam power engineers think of their work in terms of so many heat units received, so many usefully applied, so many lost. What is lost must if possible be traced and recorded as well as what is used, and the quest for efficiency is an endless endeavour to eliminate the losses. The reader will recollect that in steam boilers one method of reducing radiation losses is to speed up the rate of combustion ; and the high-speed engine we saw originated with an attempt to reduce losses due to steam parting with its heat to the cylinder walls.

Now imagine steam being led from a boiler to the interior of a turbine casing through a nozzle, or, if you like, several similar nozzles. Within the casing is a wheel equipped with vanes or blades at the rim. Steam, we will assume, is expanded to the fullest possible extent in the nozzles. It acquires velocity and, impinging against the blades, spins the wheel round. Kinetic energy in the steam is thus transferred to the wheel, further losses taking place in the process. The transition from heat energy in the steam, to kinetic energy in the wheel, is now complete. It will be clear that under ideal conditions, without losses, the difference between the quantity of heat in the steam upon admission to the turbine, and the quantity left in it at the exhaust, would be an accurate measure of the work done in rotating the turbine wheel. This difference between heat at admission and heat at exhaust is known to physicists and engineers as " heat-drop." Only by thinking in terms of heat-drop is it possible to get a clear idea of the limits of thermal efficiency in a steam turbine. Though, as already stated, there are losses, many of which can be only partially eliminated, every effort is made to approach ideal conditions. Engineers benefit enormously by keeping such ideals clearly in front of them ; and no one thinks of calling them " utopian idealists " because they seek a perfection which can never be realised. Some day, perhaps, the affairs of all mankind will be planned and guided by comprehensive ideals, as an engineer is guided when designing a steam turbine.

It will now be clear why engineers seek to utilise higher steam pressures and temperatures. The importance of a condenser will also be apparent. The object in both cases is to increase the heat-drop which takes place in the turbine. We are also now in a position to understand why Parsons succeeded where others had failed. We have already noted that if all the heat energy were converted into kinetic energy by expansion in a single row of nozzles, and then applied to a single wheel, an impossible blade speed would be indicated for efficient operation. By using a number of wheels, and distributing the heat-drop over the whole of the wheels step by step, the steam (and therefore the wheels) in the Parsons turbine only acquired comparatively little velocity at each step. Thus a moderate speed combined with efficiency became possible.

In the Parsons machine, as since developed, each ring of moving blades receives the impact or impulse due to jets of steam directed against it by a preceding ring of fixed blades. But, in addition, the steam expands as it threads its way through each ring of blades ; so that its velocity is not only altered in direction, but is increased relatively to the blade surfaces over which it moves. This produces a reaction effect as in Heron's eolipile, or—to give a modern example—as in a sky-rocket. The Parsons machine might therefore be called an impulse-reaction turbine, although it is almost invariably referred to—rather loosely—as a reaction machine.

A few years after the successful results achieved by Parsons, another inventor, Gustav de Laval, produced a single-wheel impulse turbine in which by several ingenious peculiarities of construction he was enabled to adopt remarkably high speeds with safety. The blade-tip speed of his 300 h.p. turbine, a



(*Courtesy of Messrs. C. A. Parsons & Co., Ltd.*)

50,000 KW. Parsons turbo-generator plant at Chicago.

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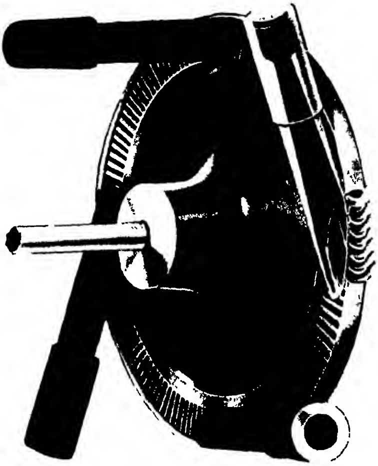
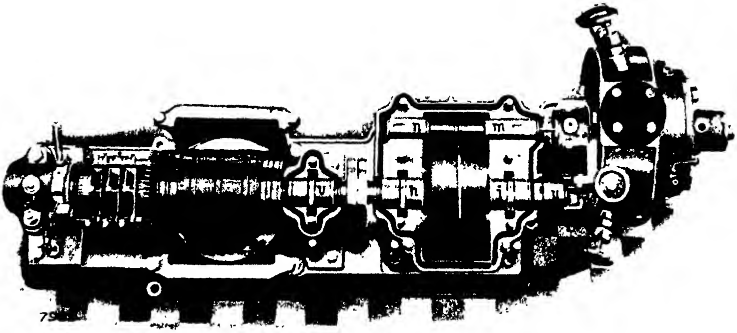


De Laval impulse steam turbine. Rotor and nozzles.



(Courtesy of Messrs. Greenwood and Batley, Ltd.)

Small De Laval steam turbine, reduction gearing, and dynamo.

size no longer made, was 960 miles an hour. In the smaller sizes the rotational rather than the linear speeds are remarkable ; a very small turbine of 1½ h.p. running at 40,000 revolutions a minute. The De Laval turbine has a wide range of usefulness in small units. Historically it is of interest primarily because it led the way to other designs, and because De Laval used a scientifically constructed steam nozzle. The passage through this nozzle first narrowed to a " throat," and then opened again gradully in the form of a cone.[1] In the De Laval turbine there is theoretically no further expansion of steam after leaving the nozzle, the pressure remaining constant across the blades.

A successful modification of the De Laval machine can be obtained by—in effect—combining a series of simple turbines in one casing, the several wheels being mounted on one shaft. With this arrangement there is a moderate drop in a first set of nozzles ; the steam passes through the blades on the first wheel at constant pressure ; then the steam is taken through a further set of nozzles where there is a further drop ; after which it passes through the second ring of blades at constant pressure ; and so on. Another development follows rather different lines. In a single wheel turbine of the De Laval type, much of the kinetic energy remains in the steam after it leaves the blades. Let us assume that the turbine runs at a still lower speed. Then still more energy would normally be wasted. But by means of a fixed ring of blades the path of the steam after passing a first wheel may be deflected back until the steam can do further work by impinging on a second ring of moving blades. But here again the steam does not expand in the blades, so that this also is a pure impulse turbine.

The difference between this machine and the one previously referred to is that in the first the *pressure* falls step by step ; whereas in that last described the *velocity* decreases step by step. Because of these characteristics the former is called a " pressure-compounded," and the latter a " velocity-compounded " turbine. Both ideas may be combined in one machine, which then receives the rather formidable name of "pressure-velocity-compounded-impulse turbine." Machines of this type were invented by the American engineer, C. G. Curtis, whose work contributed very materially to progress in general design.

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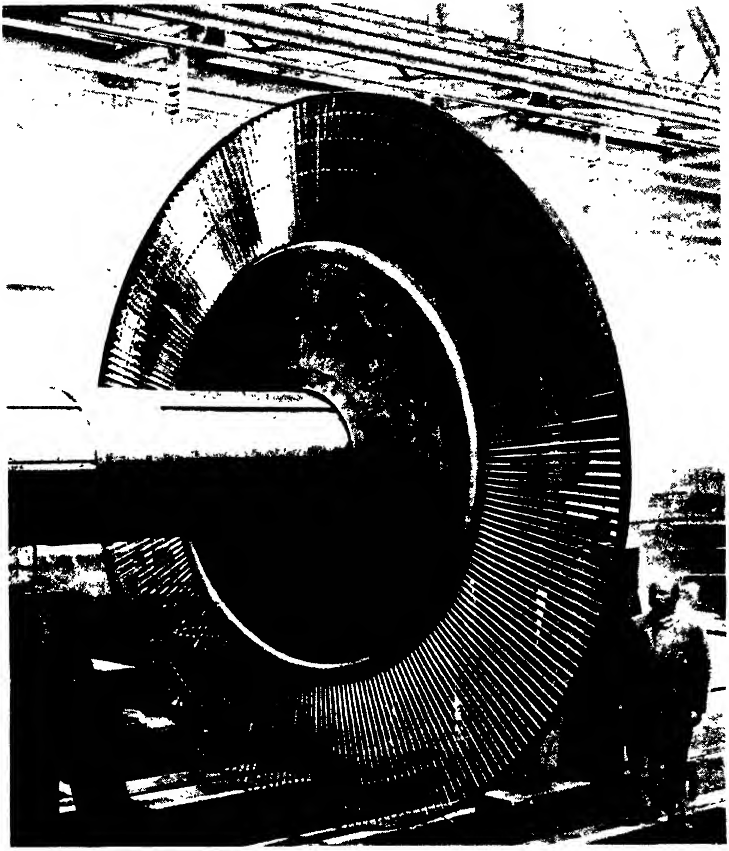
[1] The theory of this nozzle was first worked out by Osborne Reynolds in 1885. See *Proc. Inst. Mech. Eng.*, 1929, No. 4 ; paper by R. W. Bailey.

So many developments have taken place in recent years that we cannot attempt even to enumerate them, much less discuss them in detail. But the construction of all steam turbines in general use is guided by the considerations we have indicated. Among those who, in addition to Parsons, De Laval, and Curtis have contributed to progress in design may be mentioned Rateau, Zoelly, and the brothers Ljungström. The work of these and a host of other inventors and designers has resulted in the quite marvellous steam turbines manufactured at the present day. Regretfully we pass over a thousand and one absorbingly interesting features—methods of speed regulation ; the Michel thrust ; the design and fitting of blades to wheels and of wheels to shafts ; developments resulting in reduced cost of construction and ever fuller use of heat energy ; refinements which ensure greater reliability and lower maintenance charges ; the never-ending process of simplification which now makes it possible to put plant with an output of 50,000–100,000–200,000 h.p. and more under the control of a few men, whose normal expression is one of peaceful preoccupation. . . . We must pass on to an examination of modern condensing plant, but before doing so we may pause to sum up a few of the advantages of the steam turbine.

Above sizes of about 500 h.p. the modern turbine is more efficient than any reciprocating steam engine, except perhaps a type known as the Uniflow. Owing to the limitations of this engine, however, we may ignore it for purposes of general comparison. The turning effort applied in a turbine is constant, so that the speed does not tend to fluctuate as in a steam engine. This fact makes the turbine an ideal prime mover for driving electrical and other machinery where steady running is essential. Reciprocating motion is entirely eliminated. Vibration is reduced to a minimum. No internal lubrication is required, and there are far fewer wearing parts than in an engine. Finally, the steam turbine involves less foundation



(*Courtesy of Messrs. Brown, Boveri & Co., Ltd.*)

Low pressure wheel and blading, 160,000 KW. steam turbine.

To face p. 160.

work, and occupies much less space than a steam engine. This has reacted on the construction and comfort of steamships to a remarkable degree, besides leading to marked economies on land in bricks, mortar, concrete, steel and other building materials.

3

Condensers and their Auxiliaries

Except for the work of a few pioneers, condenser design thirty years ago was very largely according to rule of thumb.[1] Now it has become almost a science in itself, and every designer benefits by the accumulated knowledge accessible to all. For this accelerated progress steam turbine development is responsible to a degree which can hardly be over-estimated. But here again we must bear in mind that the primary consideration with designers is the ideal of highest possible thermal efficiency.

The most important function of a steam condenser is to reduce the exhaust pressure of a turbine or engine, thus increasing the heat-drop available in the prime mover, and with it the amount of work done by the steam. At the exhaust there is still some heat remaining in the steam, and this is removed so far as possible by the use of cooling water in the condenser. In high-efficiency plants the condensed steam is returned as hot water to the boilers. Several types of condenser are manufactured. In the jet condenser steam is brought into intimate contact with jets or sprays of cooling water, the condensed steam subsequently being pumped away with the cooling water. This " condensate " is not used in the boilers, so that heat is to that extent wasted. Another type is the ejector condenser. This also is a heat waster, and although both jet and ejector condensers have their uses, we shall not describe them in detail, turning instead to the surface condenser which is the most efficient and most widely used type of all.

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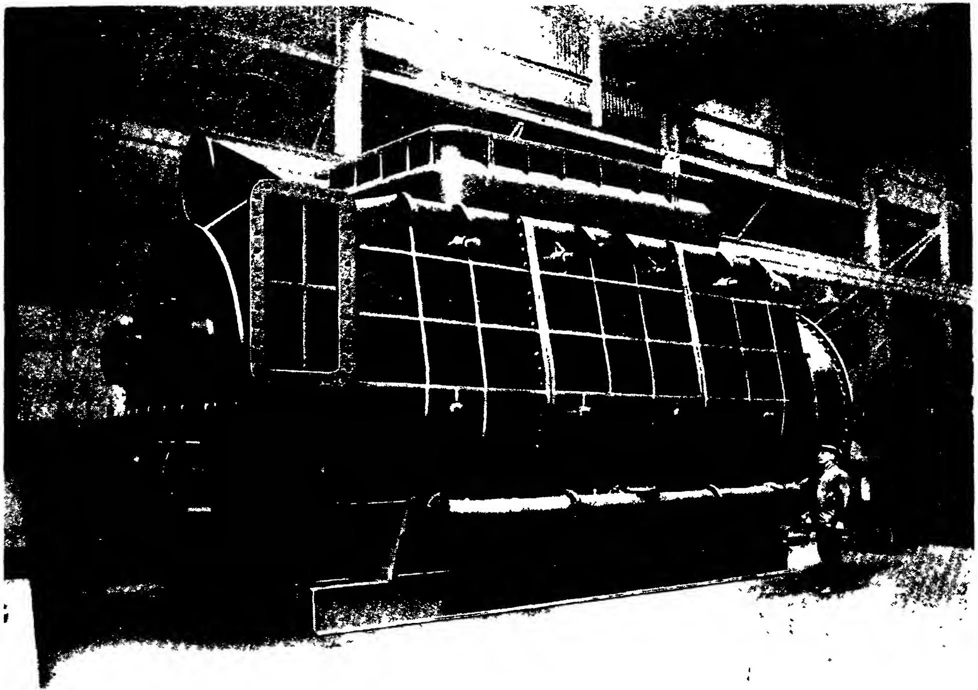
[1] In 1902—3 an exhaustive series of investigations was carried out with an elaborate experimental surface condensing plant, particulars of which will be found in a paper on " Surface Condensing Plants and the Value of the Vacuum Produced," by R. W. Allen, before the Institution of Civil Engineers, February 29, 1905.

In general a surface condenser consists of a number of brass tubes fixed inside a cast-iron or steel shell. The ends of the tubes are secured to brass division plates, which being fixed at some distance from the ends of the shell, divide the whole condenser into three compartments. The middle and largest compartment contains the tubes, which communicate with both end spaces. Cooling water is admitted at one end, passes through the tubes, and leaves the condenser at the other end. The central portion also has connections, by one of which exhaust steam is admitted from the turbine to make contact with the tubes. This connection is usually at the top, since it is found convenient in practice to place the condenser directly under the turbine exhaust ; an arrangement which can, however, be modified as may be desirable. The condensed steam falls to the bottom and is then conveyed away to a convenient receptacle known as the " hot-well," or in more up-to-date practice is taken directly to the boilers.

Steam occupies very much more space than the water from which it is generated, or into which it may be condensed. Thus at an absolute pressure of 1 lb. to the square inch (that is 13·7 lbs. below atmospheric pressure) steam takes up 2,080 times the space of an equal quantity of water. If the condenser is airtight, it follows that a vacuum will be created within it when in action. Now the reason why condensing plant has been so greatly improved since the coming of the steam turbine is that vacuum has a far greater bearing on turbine than on engine efficiency. In a reciprocating engine it is impossible to utilise high vacuum effectively, owing to practical limitations in the sizes of cylinders. There are no such limitations in turbine design, so that every effort is made to reduce the pressure in the condenser to its lowest possible limits. Moreover, the efficiency of a steam turbine depends more on a reduction in pressure at the exhaust than upon an equivalent increase in pressure at the inlet so long as further reduction is possible.

Shape of shell and disposition of tubes are influenced by a number of considerations. It has been found from experience

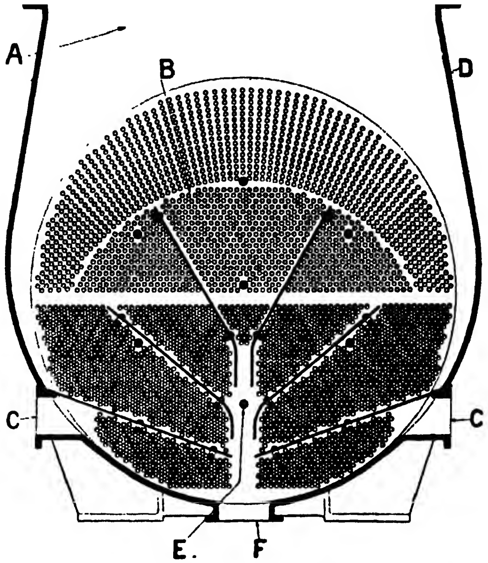


(*Courtesy of Messrs. W. H. Allen Sons & Co., Ltd.*)

A large modern surface condenser.

[*To face p. 11*

that maximum condensation takes place on tubes in the upper part of the condenser, nearest the point at which steam enters. Omission of tubes here would therefore deprive the condenser of much of its most valuable cooling surface. On the other hand it is very undesirable to obstruct the incoming exhaust steam, as this would tend to increase the pressure at the turbine exhaust above that in the lower parts of the condenser. A compromise is usually adopted, involving a very large exhaust connection, and the provision of " lanes " or passages leading downwards through the nest of tubes, and also between the tubes and the shell. Such lanes also serve another important purpose. A certain amount of exhaust steam finds its way through them directly towards the lower parts of the condenser. Here it comes in contact with condensate dripping from the upper tubes. Heat from the steam is transmitted to the



Sectional drawing of an Allen surface condenser.

A Turbine exhaust.	D Condenser shell.
B Tubes.	E Tubeplate stays.
C Air and vapour outlet.	F Condensate outlet.

condensate, which is thus kept at a higher temperature than it otherwise would be. This means higher boiler feed temperature and therefore an increase in the overall efficiency of the plant.

If an unfailing supply of cooling water is not available, then the same water must be used again and again, and must therefore itself be cooled. This is commonly effected by taking the water to the top of a tall wooden or concrete structure known as a cooling tower. Within the tower is a large number of laths, over which the water falls. As it descends it is broken up into a fine spray, and cooled either by natural draught or by using fans to force air through the tower. A pump must in any case be provided for cooling water circulation. In addition a condensate pump is required to extract the condensate against atmospheric pressure ; and an air extraction pump to remove air and vapour, to ensure that the vacuum is maintained. Yet another pump is required between the condensate extraction pump and the boilers. The function of this is to feed the boilers against boiler pressure. These pumps are now almost invariably of the centrifugal type for large power plants, except the air pump, which may be one of several alternative designs. The whole of the feed-water system between the condenser and boiler should be airtight, since boiler corrosion is primarily due to oxygen finding its way through to the boiler in the water. Exposure of hot water to the air results in oxygen being absorbed at a rate of 3 to 4 cubic centimetres to the litre.

Although we are passing now a little beyond the condenser and its auxiliaries, it may be noted here that condensate alone is frequently insufficient for boiler feed requirements, so that make-up water must be added. This should be treated to remove oxygen, and, when necessary, scale-forming impurities. Oxygen can be removed by passing water over a nest of steam-heated tubes contained in a suitable vessel. On striking the hot surfaces water is " flashed " into minute particles, the gases are liberated, and removed by an ejector. Apparatus of this kind is commonly known as a deaerator. Hard water may be chemically treated, or alternatively evaporation may be resorted to, the water being treated in an evaporator specially designed for this purpose.

4

The Quest for Efficiency

The quest for efficiency in steam-power plant began with the work of a few solitary pioneers. These pushed ahead until arrested by barriers which it fell to the lot of later generations to remove. Many followed where the few had led. Now a multitude is on the march—physicists, mathematicians, fuel technologists, metallurgists, inventors, engineers. The never-ending endeavour to surpass results already achieved has led from one development to another. No matter what the obstacles, there has always been progress in the end ; if not by one route then by another. And always the effect has been cumulative. As with a stream trickling down a mountain side, the flow might be temporarily arrested and lost in some seemingly stagnant pool, only to find its way onward again presently with renewed energy. Later the streams united to become rivers. Now the rivers have in their turn come together to form a mighty flood which sweeps away old landmarks of design and construction even as we pause to examine them. The pace has indeed become terrific. The most revolutionary changes are taking place in the production of power by steam. But now those who are in the van find that they are approaching barriers far more formidable than any so far encountered. It may be that we are already in sight of definite limits to further progress along routes hitherto followed. If so we may expect a momentary halt in the forward movement until other channels of progress have been successfully explored.

Let us consider three obstacles to the further development of steam power plant on conventional lines. It is impossible to carry vacuum in a condenser beyond absolute zero of pressure. In practice we cannot reasonably expect to approach zero within, say, a quarter of a pound. There are, however, condensers now working at less than half a pound absolute pressure. Owing to practical considerations there is no advantage to be gained by attempting to improve on this figure. So much for barrier number one.

Two other limits are imposed by conditions accompanying high temperature. At 900° F., approximately the highest temperature at which steam is being generated on a commercial scale, the heat in the tubes begins to produce dissociation of the steam which they contain. This process increases rapidly with any further rise in temperature. Steam, as such, no longer exists; being replaced by hydrogen and oxygen. Hydrogen tends to penetrate metals at high temperatures, while oxygen causes oxidation. It will be conceded that we have here a problem of some magnitude.

Finally, there are temperatures at which ordinary metals become unstable, unreliable, unsafe, unusable. At 750° F., a fairly common temperature now in large power stations, we are beginning to approach this stage. At 900° F. special metals become necessary; nickel-chrome and high chromium steels being used—metals which among other valuable characteristics possess that of resistance to oxidation. Nevertheless, the use of such metals is severely limited by first cost, and particularly by cost due to manufacturing difficulties. But even if 900° F., or possibly 1,000° F., could be reached by a large number of power stations, the fact remains that still further progress in this direction is not anticipated for the present by some at least of those most competent to judge.

These are the major difficulties which now have to be faced. But even to approach such limits involves the solution of an almost inexhaustible supply of other problems. In the endeavour to eliminate the difficulties encountered new designs of plant are being adopted, new features are being incorporated, making power stations obsolescent within a few years of their completion. In ten years steam pressures have increased in many large plants from 250 to 600 lbs. to the square inch. A number of boilers with pressures ranging from 750 to 1,400 lbs. have been installed, and even boilers generating steam at 1,700 lbs. to the square inch are in successful operation; while novel designs, such as the Benson boiler, operate at pressures exceeding even these high values. Concurrently with increase in pressures has come a remarkable increase in unit capacity. Lancashire boilers are capable of generating about 9,000 lbs. of steam an hour under favourable conditions. A capacity of 300,000 lbs. of steam an hour in a single unit has been reached by water-tube boiler manufacturers. Apart from increase in size the most notable of recent developments in the boiler house are the more general use of pulverised fuel, the adoption in some cases of water-cooled walls for combustion chambers, a tendency to eliminate economisers, the adoption of large-scale preheaters for heating the air before it enters the furnace, and in general the complete substitution of machinery for muscle. In the power house changes are also taking place. Large turbines are being divided up into sections, so that high pressure and temperature conditions can be dealt with in what is in effect a separate high-pressure " cylinder." The density of high-pressure steam at the turbine inlet, and the huge volumes of low-pressure steam at the exhaust, are matters noticeably affecting design. Steam is now in a number of turbines being reheated after leaving the high-pressure cylinder. Where this is done by taking steam to a reheat boiler and then returning it to a lower pressure section of the turbine, there is clearly a tendency to bring the turbine room into more intimate connection with the boiler house. In time the wall between the two may disappear. Already it is little more than a relic of the old, wasteful, man-handling, stokehole days.

These are a few of the changes recently made or now taking place. As the limiting conditions we have indicated are approached, the difficulties to be contended with increase in number, variety, and complexity out of all proportion to the advance achieved. It will be clear that an enormous amount of thought, time, money and courageous experiment are now required to secure even the slightest additional gain in efficiency. And with all this effort the highest overall thermal efficiency can *on present lines of development* never be much more than about 30 per cent. That is to say, about 70 per cent. of the heat units in the fuel consumed are wasted even under the most favourable conditions. This is primarily due to the fact that approximately 1,000 B.Th.U.'s of latent heat are lost in warming the condenser cooling water for every pound of steam condensed. A little of this latent heat is now being saved by taking steam from the turbine at various points, after it has done much of its work, to heat the feed-water. This means a greater steam consumption, but the overall efficiency of the plant as a whole is increased. Yet most of the latent heat is still thrown away. At present it is not fashionable in engineering circles to talk about this waste of over two-thirds of the heat produced from the fuel we burn. Some day, perhaps, a genius will come along and show us how to make effective use of this heat now being lost, and mankind will sweep forward again to achievements at present beyond our ken. One fact is worth recording. As steam pressures increase the latent heat decreases. At some point, therefore, there will be no latent heat; only sensible heat directly usable in a steam turbine. The necessary pressure appears to be somewhere about 3,200 lbs. to the square inch. It is just possible that very considerable progress may eventually be made in this direction.

Work on strikingly novel lines has been undertaken in America by the General Electric Company with plant using mercury vapour instead of steam. The chief advantage of this process lies in the fact that the latent heat of mercury forms only a relatively small part of the total heat. The mercury is vaporised in a special boiler, while the mercury condenser acts as a boiler for generating steam used in a separate turbine. It has been calculated that the over-all thermal efficiency of such a plant may be as high as 41·5 per cent. Although the process has long passed its experimental stage, and its practicability has been demonstrated, it is impossible yet to say that the substitution of mercury vapour for steam is likely to be made on any extended scale. Yet it is conceivable that the use of either mercury or of some other material—diphenyl oxide has been suggested—may lead sooner than is generally anticipated to unprecedented levels of efficiency in ordinary power station practice.[1]

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[1] Writing in 1841, Ewbank recorded in his *Hydraulics and Mechanics* (p. 474) that "the vapor of mercury has been tried as a substitute for steam, but without much success."

Dr. W. R. Whitney, Director of Research and Vice-President, the General Electric Company, U.S.A.

[*To face p.* 168.

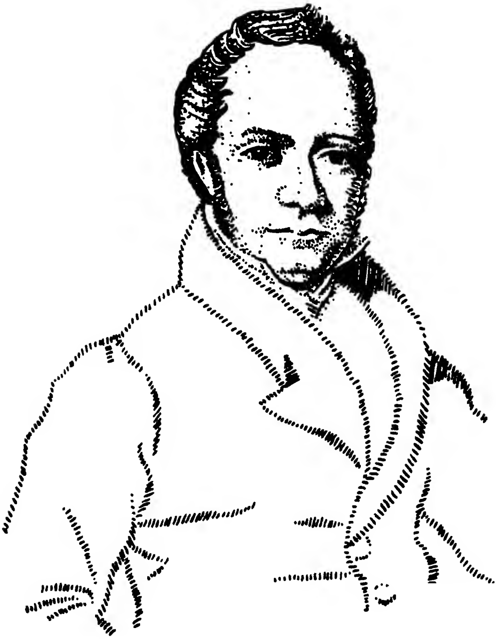
CHAPTER III

INTERNAL COMBUSTION ENGINES

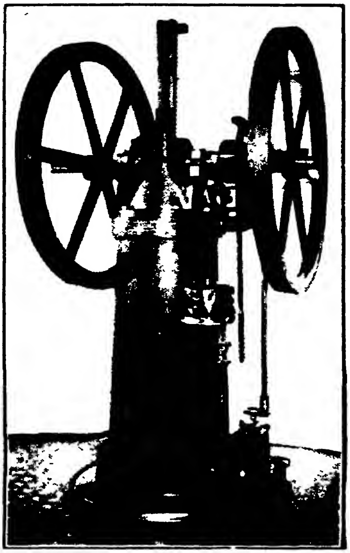
I

Early Projects and Achievements

We have seen how easily heat is lost on the way from a boiler furnace to an engine cylinder or a turbine casing. Nothing could be more natural, therefore, than that from early times men should have tried to burn fuel within the cylinder itself. Nevertheless, early experimenters failed to construct a satisfactory engine, and although attempts were made in the later part of the 17th century to use gunpowder for ordinary motive purposes, we hear of little further development for over 100 years. The pressure due to combustion of gunpowder increases too rapidly for satisfactory use in an engine. But even if this difficulty could have been overcome, it is more than doubtful whether the engineering knowledge of those days was equal to the construction of suitable cylinders and transmitting mechanism. Most machinery was then, and for long afterwards, constructed on the crudest lines. Wood with iron fittings was used wherever possible, and it was not until early in the 19th century that all-metal machinery came into general use. Moreover, the minds of most men were diverted throughout the 18th century to the possibilities of steam. But from about 1780 onwards we begin to hear of experiments being made with coal gas, culminating in practical demonstrations of its use for lighting purposes by William Murdock at Redruth in 1792, at Neath Abbey in 1796, and at the Soho Foundry on behalf of Boulton and Watt in 1803. At the same time it became evident that here was a more suitable source of power than gunpowder. The internal combustion engine again became the subject of experiment, and it is of considerable interest to note that one of the earliest attempts took the form of a gas turbine. In 1791 John Barber obtained a patent according to which he proposed to use gas or vapour from coal, wood, oil or any other combustible matter, to be distilled in a retort and " mixed with a proper quantity of atmospheric or common air." The gas was to be used to rotate a wheel equipped with vanes, the products of combustion being released through a suitably placed orifice. In 1794 Robert Street outlined proposals for an engine with piston and cylinder, the piston being used to draw air into the cylinder and flame ignition being adopted. In 1801 an inventor named Le Bon, who had already played a part in the early evolution of gas lighting, drew attention to the desirability of compressing gas and air before ignition in an engine cylinder. The engine was double-acting and fitted with electric ignition. Another



Samuel Brown, from an old engraving. Brown's patents are dated 1823 and 1826.



Vertical atmospheric gas engine, 1869

(*Courtesy of Messrs. Crossley Bros., Ltd.*)

Otto horizontal slide gas engine, 1876.

[*To face p.* 171.

Frenchman, De Rivaz, also made use of electric ignition about this time.

During the next fifty years a large number of patents were taken out. The Rev. W. Cecil read a paper in 1820 in which he gave an account of the first gas engine which actually worked. Samuel Brown devised a gas engine which in 1832 was used for pumping purposes. It had already been adapted to boat propulsion. The first commercially successful engine was produced by a French inventor, Lenoir, in 1860. The engine was defective, design being dominated by steam engine practice. After a brief popularity this engine fell into disfavour, owing to faulty construction and an extravagant consumption of gas—100 cubic feet per horse-power per hour. In 1862 gas engine design was, for the first time, approached on scientific lines. Beau de Rochas formulated what has since been called the Otto cycle, involving four strokes to each impulse imparted to the piston. In his specification de Rochas enumerated four conditions essential to successful operation—the largest possible cylinder volume contained by a minimum of surface, the highest possible speed of working, maximum expansion, and maximum pressure at the beginning of expansion. Guided by these principles, Otto, in 1876, produced his now famous " silent " engine. No doubt it seemed silent enough to those accustomed to the pandemonium characteristic of its predecessors.

The Otto engine was of the single-acting type, arranged either for horizontal or vertical working. During the first outward stroke of the piston, gas and air were drawn into the cylinder. On the return stroke the mixture was compressed into a clearance space and then ignited, after which the only working stroke in the cycle was made under pressure of the burning gases. The piston then returned once more, sweeping out the spent products of combustion. Originally admission of gas and air was controlled by an ordinary slide valve. Later this was replaced by the " mushroom " type of internal combustion engine valve with which everyone is now familiar. When the Otto patent expired in 1890 other firms adopted this cycle of operations, which thus came into almost universal use ;

although the invention of a "two-stroke" cycle engine in 1882, by Dugald Clerk, led to the development of several very successful gas engines designed on this basis. In these engines the piston receives an impulse every revolution.

During early stages of development gas engines were only built in small sizes—mostly under 20 h.p. Coal gas was the only fuel available, and the cost of this was excessive for power purposes. In 1881 J. E. Dowson made use of a cheaper form of gaseous fuel, obtained by the partial combustion of anthracite in a vessel which he called a producer. This process has since been widely used, the product being universally known as "producer gas." In 1895 a further step was taken when B. H. Thwaite demonstrated that gas engines might be driven by the use of blast-furnace gases hitherto wasted. The production and use of cheap gas gave a great impetus to gas engine manufacture.

As small Otto-cycle engines approached standardisation they began to take the general form with which many readers will be familiar. As now made, the cylinder is water-jacketed, the cooling water circulating through large cooling tanks. The inlet and outlet valves are operated by cams on a side shaft. This shaft is geared to run at half the speed of the crankshaft so that the sequence of operations shall take place during two revolutions of the engine. Speed is regulated by a centrifugal governor which controls admission of gas on small-size engines, and the quantity of explosive mixture taken in during each cycle in larger sizes. Since there is only one impulse to every four strokes, a heavy flywheel is required to keep the parts moving and to reduce cyclic variations in speed. Work is only done on one side of the piston, the cylinder being left open at the other end. The piston is linked directly to the connecting rod without the intervention of a piston rod and cross-head.

The first successful oil engine was made by the brothers Priestman in 1888, although effective pioneer work had already been done by G. B. Brayton in America. There is very little difference in general construction between small gas and oil "Otto" or four-stroke engines. The main difference lies in the fact that liquid fuel must be vaporised before use. When the liquid is sufficiently volatile to evaporate without the application of heat, a simple spraying device called a carburettor suffices to secure an explosive mixture, as in a petrol engine. But paraffin has a higher flash point ; that is, the oil only begins to give off vapour at a higher temperature. Consequently a vaporiser is required. This consists of an extension to the cylinder, kept at a fairly high temperature. Movement of the piston draws air and oil into the vaporiser, and an explosive mixture of hot air and vaporised oil is formed for combustion in the cylinder.

Early Otto-cycle engines were often used for driving dynamos, though anything less suited for this purpose it would be difficult to imagine. With only one impulse every four strokes, and dependence upon the momentum of a flywheel to keep the engine going in the meantime, also with a " hit and miss " governor and frequent misfiring in the cylinder, it was almost hopeless to expect the steady running so necessary for electric lighting. One who has had extensive personal experience with the earlier makes of engine remarks :

> " The gas engine of the period was noisy, spasmodic and pestilential. In many respects it resembled the late Mrs. Gamp and the late Mrs. Betsy Prig. It would do nothing unless it felt so disposed. After imbibition it suffered from violent eructations, and to rouse it from its repose on a cold winter's morning,—well, even horses couldn't move it. What the reputation of electric lighting suffered from the early gas engine ! " [1]

But gas engine makers have made great progress since those early days. One defect after another has been eliminated, one improvement after another has been incorporated, with the result that gas engines are now made to run as smoothly, as quietly, and as reliably as any other type of internal combustion engine.

2

Further Progress in Design

The lot of the designer of internal combustion engines is not altogether a happy one. Ask him to explain in simple language just what he is about and he will eye you rather blankly. Then, after a pause, he will talk rapidly about adiabatic and isothermal expansion, ratios of specific heats and of compression, entropy and the thermodynamic relations of a perfect gas. Usually, too, he produces complicated charts and diagrams and wanders off into highly intricate calculations. It is all very mystifying to the layman, who as often as not finds himself, like Omar Khayyam, coming out by the same door as in he went. The fact is that internal combustion engine design really is a complicated business, certainly more complicated in many ways than designing a steam engine. Considerable information is available about the ways of steam. Experience has been accumulated and men have now learned to handle it with some degree of assurance. But though much research has been carried out to ascertain the various ways in which combustible gases will behave when compressed in an engine cylinder, and how they will unite on combustion, further investigation is required before really satisfactory theories and principles can be formulated. The fuels used cover a fairly wide range of chemical and physical properties ; and the whole process of producing from them an efficient mixture, compressing it, firing it, generating heat from it, converting a portion of that heat into work, transmitting some of the balance through metal walls, and rejecting the remainder with the spent products of combustion, has to be carried out either in the working cylinder or in close association with it. Moreover, internal combustion engine temperatures cover a much wider range than steam engine temperatures. Momentarily, the gases in an internal combustion engine cylinder may reach 3,600° F. or more. Very special precautions must accordingly be taken to keep the average temperature within safe working limits. Hence the care taken to ensure rapid heat transmission by means of water-jacketing and cooling arrangements, in contradistinction to the efforts of the steam engineer to reduce radiation losses.

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[1] " Early Days in the Electrical Industry," *The Electrical Times*, 1921.

Few people clearly visualise the extraordinary events occurring within the cylinders of gas, oil, and petrol engines. The silent engine which apparently without effort propels a motor car at forty miles an hour and more contains within each of its cylinders a raging, fiery furnace. Were the maximum temperatures of combustion maintained, the cast iron of which the cylinders are made would melt and flow like metal pouring from a cupola. Even platinum, the most infusible of metals, melts at about 3,000° F., well below the maximum temperatures reached in most internal combustion engines. For observation purposes Sir Dugald Clerk fitted to a gas engine cylinder a " window " of very thick glass, and was thus enabled to note that the gases reach a dazzling white heat.

When an explosive mixture is ignited, a flame spreads in all directions from the point of ignition. This flame takes time to travel, so that each portion of the mixture ignites in turn. The rate at which it travels depends on the pressure, and also on the proportion of gas to air. At a low initial pressure, and with a weak mixture, combustion takes longer to extend to the parts remote from the point of ignition. With the spread of combustion more and more heat is evolved, temperature and pressure both rising together. There are various highly important factors involved in this process, but the most important is the effect of compressing the mixture before ignition.[1] It is a well-established fact that the rise of pressure due to combustion takes place much more rapidly when a highly compressed mixture is used. This, of course, reacts directly upon the power developed by the engine.

But compression is important for other reasons. Calculation shows that increases in compression lead in an Otto-cycle engine directly to increased thermal efficiency, apart from considerations involving the degree to which gas and air are mixed and the rate at which combustion is propagated. As might be expected, therefore, a large part of the progress in design that has been made in recent years, apart from the evolution of new types, is due to the adoption of higher compression pressures. Early Otto engines seldom converted into available power more than about 14 per cent. of the energy supplied in the fuel. With increased ratios of compression the efficiency has increased until the return is now between 30 and 32 per cent. Of the balance, about 43 per cent. is rejected with the exhaust gases, and 25 per cent. is taken away by the cooling water and by radiation from the engine. Of course it must not be supposed that the advance made in efficiency is wholly due to higher compression, but there can be no doubt that without it modern internal combustion engines would be far less efficient than they are.

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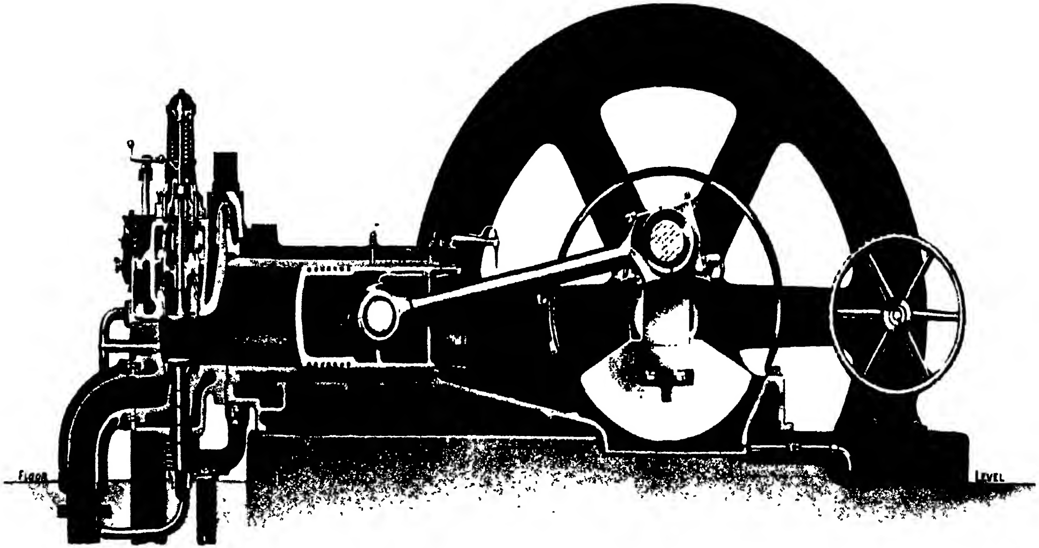
[1] Barnett in 1838 took out a patent in which attention was first drawn to the advantages of compression.

But there is a limit to the process of getting more work out of an engine by this means. As the gases are compressed their temperature rises, and presently a point is reached at which "spontaneous combustion" takes place. Owing to the variable nature of the mixture in an Otto-cycle engine, it is quite impossible to control the timing of ignition under such circumstances. For some time after higher compression pressures were first adopted attempts were made to keep down the temperature in gas engines by injecting a spray of water into the cylinder, either during the suction stroke or at the commencement of compression. This, however, introduced new difficulties and the practice was eventually discontinued. Although compression is thus seen to be a matter of first importance, the underlying fundamental consideration of design, as with all heat engines, is the difference in temperature of the working medium before and after work is performed by it. It is this temperature difference which alone makes the performance of useful work possible. The first requirement in order to predict the performance of a gas engine is therefore to know the rise of temperature due to the explosion. This rise of temperature, which, as we have seen, is directly affected by compressing the mixture, is of course accompanied by a rise of pressure which thereupon moves the piston through its working stroke. It will be realised that since the increase in temperature and pressure takes place almost instantaneously, reaching a maximum at a time when the working parts are still in effect stationary, the whole construction of the engine must be on very robust lines. The cylinder, which in early horizontal designs was allowed to overhang, is now supported over its whole length. The centre of the crankshaft is kept as low


FLOOR
LEVEL

(Courtesy of Messrs. Crossley Bros., Ltd

Section of a modern gas engine, 100 brake horse-power.

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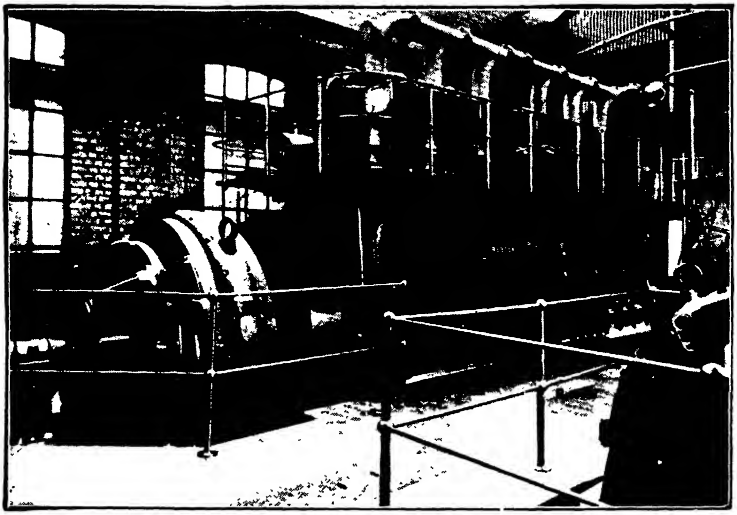
as possible, thus increasing stability and reducing vibration. Not only the cylinder, but other parts subjected to heat are now water-jacketed. In years gone by fractured crankshafts were a cause of considerable anxiety to gas engine designers. Now it is possible to avoid practically all risk of this trouble by fitting a substantial flywheel, supported by an outer bearing ; the crankshaft and its main bearings being also suitably proportioned.

The general trend of departures from precedent in recent years may now be indicated very briefly. It is a remarkable fact that though no strikingly new developments have taken place in gas-engine design, so many types of engines running on liquid fuel have been evolved, and there are so many variants on each type, that rigid classification has become impossible. Here we shall not even attempt to enumerate all the kinds of oil engines now in use. Leaving volatile spirit engines and Diesel engines for later consideration, we propose to confine ourselves to a brief survey of the main lines of oil engine development.

In 1886, as we have already recorded, the Priestman oil engine was patented. In this the vaporiser was heated by the exhaust gases from the engine. With other early oil engines a lamp had to be kept burning the whole time to heat the vaporiser. The compression pressures were low and the fuel consumption high. Only refined oils such as paraffin and kerosene could be used. Next came an engine capable of using the lighter crude oils. No lamp was required after starting, the heat developed during compression being sufficient to ignite the charge. The inventors of this engine were H. Akroyd-Stuart and C. R. Binney, who took out a joint patent in 1890. This represented a great step forward, and modern oil engines have been evolved to a large extent from the " Akroyd " engine. But still the fuel consumption was high —about 1 lb. per brake horse power per hour—primarily because a moderate degree of compression could not be exceeded without pre-ignition taking place. In this connection it should be noted that the fuel was sprayed into the vaporiser during the suction stroke. A lamp was still necessary when starting the engine.

A new type, known as the hot-bulb engine, appeared about 1910—the vaporiser forming a bulb-like extension to the top of the cylinder and being connected to it by a narrow passage. Ports in the cylinder, opened and closed by the piston, replaced the ordinary mechanically operated valves. With this it was possible to adopt higher compression pressures, leading to a further reduction in fuel consumption. But a heating lamp for starting purposes was still essential. Then experiments were made with fuel injection at the end of the compression stroke, instead of during the suction stroke. This injection—known as solid injection or airless injection—was not by means of air blast, as adopted by Diesel, but made with a mechanical pump and sprayer. It was now found that sufficient heat could be generated during the compression stroke of the piston to ignite the fuel oil without any external heating. In other words, the engine could be started up from cold without using a lamp, although heavy crude oil was used ; hence the name " cold starting engine " which is sometimes applied to it.

Since then considerable progress has been made with this, the most modern type of oil engine ; accompanied by a remarkable reduction in fuel consumption to about 0·4 of a lb. per brake horse-power per hour. The development of this engine cannot be attributed to any one inventor. It is the joint product of a large number of ingenious engineers, many of whom have for years been working independently along similar lines. One of the most distinctive features of this new engine is the fact that ignition depends on several causes, instead of only upon one. This involves much more careful design and balancing of the various factors involved than in engines depending for ignition upon, say, a spark plug, or even a hot bulb. There can be little doubt that the so-called solid-injection engine has a considerable future before it, either in its present or some even more highly developed form. Considering the difficulties in the way of starting without any external heating device when running on crude fuel oil, this engine may legitimately be regarded as a remarkable triumph of applied science and engineering skill. Engines of this type are already



(*Courtesy of Messrs. Ruston and Hornsby, Ltd.*)

Six-cylinder vertical oil engine, 840 brake horse-power.

[*To face p.* 178.

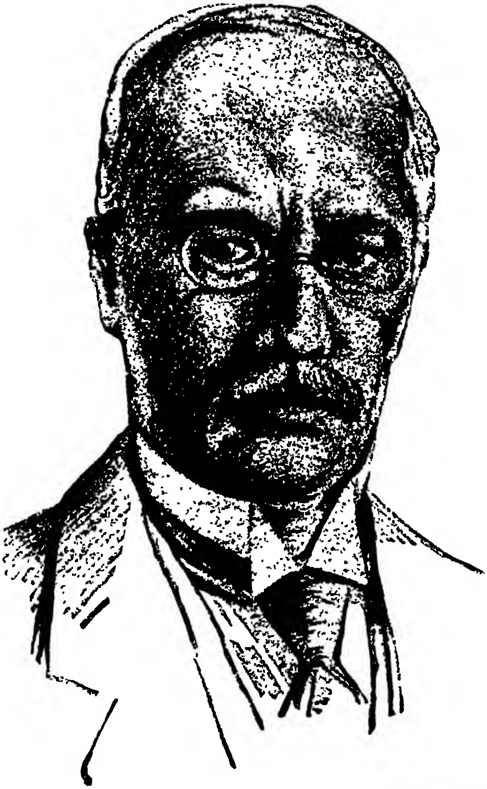
being developed, with every prospect of success, for the propulsion of both automobiles and aircraft.

Two other modern developments must be noted here. One is the Humphrey gas pump, and the other the Still engine. Of the Humphrey pump we shall content ourselves with remarking that it has no piston, that the pumping action is obtained by direct explosion pressure on the surface of the water to be pumped, and that the whole thing is an embodiment of highly ingenious and original ideas. The engine invented by W. J. Still is also remarkable for the ingenuity and originality shown in its development, though the underlying idea is not new. Briefly, it consists of an internal combustion engine, steam being used to do work on the underside of the piston. This steam is generated by the heat which would otherwise be lost in the water-jacket and exhaust gases. The possibilities of this engine are great. At present it has a demonstrably higher thermal efficiency than any other type of prime mover, utilising as much as 44 per cent. of the heat generated by the fuel. A courageous attempt has been made to incorporate the Still engine in a new design of railway locomotive, but much experimental work remains to be carried out before it is likely to come into general use, either for this or for ordinary industrial purposes.

The Diesel Engine

Rudolf Diesel was born in 1858. At the age of twenty he was already thinking of the possibilities of a new type of engine. During his training at the Polytechnic Munich he had learned that the steam engine only transformed 6 to 10 per cent. of the available heat of the fuel into effective work. This had left a strong impression on his mind, and he made a note to see if some more efficient use of the available heat might be made in an engine designed on new lines. Thus it is clear that his scientific training enabled him from the first to think in terms of heat received, heat used, and heat rejected. In this he had an incalculable advantage over his rule of thumb contemporaries; that is to say, over the majority of his fellow-engineers. Without reasoning based on scientific principles the Diesel engine could never have been evolved.

In 1892 he applied for his main patent and in the following year the practical work of development was begun. After several years of research and experiment—much of which was both tedious and discouraging—an engine capable of giving satisfactory service was at length built at Augsburg in 1897. The strikingly original turn of the inventor's mind may be gauged from the fact that at first he attempted to build an



(*Courtesy of the A. E. G.*)

Rudolf Diesel, 1858–1913.

(Courtesy of A. E. G.)

The first Diesel oil engines, exhibited at Munich, 1898.

engine to run on coal dust. To some such engine we shall probably come in the future, but it was at that time too big a step to take, and Diesel was forced to abandon the project ; turning instead to crude oil which offered a more immediate prospect of success.

From 1897 onward continuous effort was made to render the Diesel oil engine suitable for ordinary commercial service, and by the beginning of the 20th century a considerable measure of success had been achieved. Thereafter the story of the engine is one of unceasing progress. Diesel himself did not live to see the merits of his invention universally recognised. One night in 1913 he disappeared at sea, while crossing to England. What happened to him it is impossible to say. He was never seen again. Of this remarkable German inventor and engineer we may say, as was said of Christopher Wren : " If you seek his monument, look around you." For no engineer of his generation contributed more effectively to man's conquest of external power, and engines made in accordance with his ideas may now be seen in every civilised country in the world.

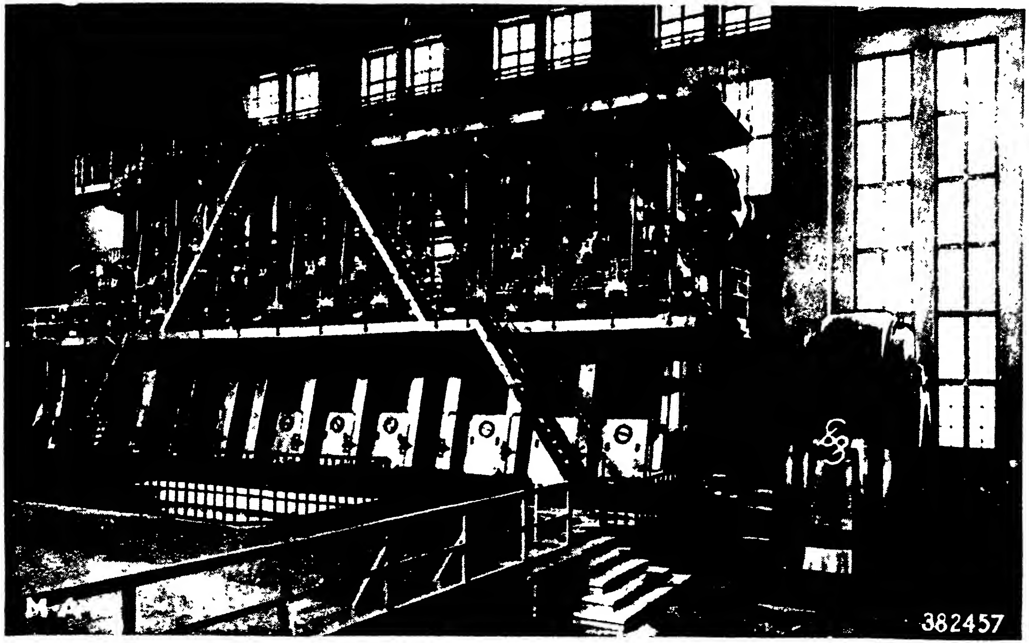
The essential difference between the Diesel engine as originally developed, and all other types of oil engine, lies in changes made in the method and use of compression. In the Diesel, air only is compressed ; and the compression is carried to such a point that the corresponding rise in temperature is sufficient to start combustion when fuel oil is introduced. Owing to the high pressure adopted, a still higher pressure must be used for injecting the fuel. Hitherto in the majority of Diesel engines this has been done by the use of a high pressure air blast. But contemporaneously with the development of the airless injection engine referred to in the previous section, new types of Diesel engine have been evolved. One of these is, in fact, an airless injection engine built on Diesel lines, so that it is now practically impossible to differentiate between the two types.

The cycle of operations in the four-stroke Diesel is as follows : First comes the suction stroke, during which air only is drawn into the cylinder. On the return stroke this air is compressed to about 500 lbs. to the square inch. The compression ratio—that is the ratio of pressure before and after compression—is about 14 to 1. Near the end of this stroke fuel is introduced by air blast and ignited, the piston then being forced out again on the combustion stroke. The injection of fuel continues for a portion of this stroke, the fuel burning at approximately constant pressure.

This process differentiates the Diesel engine proper from other oil engines in which combustion takes place at constant volume; that is, before the piston has begun to move. Throughout the remainder of this stroke the gases expand, so that the action more nearly resembles that of a steam engine, which works expansively after the incoming steam has been cut off. When nearly at the end of the combustion stroke the exhaust valve opens and the products of combustion are expelled from there onward until the end of the next stroke.

It will be seen that several auxiliary pieces of apparatus are essential to the operation of the four-stroke Diesel as originally evolved. An air compressor is necessary to provide the air blast, and blast-air reservoirs are also essential when the compressor is driven by the engine itself. In addition, a fuel pump, controlled by the governor, is required to supply oil at a pressure exceeding that of the air blast. The oil enters the combustion chamber through a nozzle which delivers it in the form of a fine spray when the air blast is operating. The pressure at which the fuel valve works may be about 1,000 lbs., and that of the air blast about 800 lbs. to the square inch. Because of the high pressure at which they operate, Diesel fuel pumps require to be very carefully designed and made.

In general, it may be said that four-stroke Diesel engines with separate compressor, as usually made hitherto, are more complicated than most other oil engines. On the other hand, they have a high thermal efficiency. The Still engine, with a higher efficiency, is even more complicated. The truth is that inventors are constantly seeking to design prime movers with a high thermal efficiency, and in doing so they very often introduce complexities which are objectionable from the point of view of cost and operation. As Carnot pointed out in his



(Courtesy of A. E. G., Berlin.)

15,000 brake horse-power Diesel engine at Hamburg Electricity Works.

[To face

famous essay on The Motive Power of Heat: "Thermal efficiency is only one of the conditions which must be satisfied by a heat-engine." And so engineers set to work to get rid of the complexities without reducing the thermal efficiency. In this way progress is usually made, and in this way remarkable progress in Diesel engine design has been made in recent years. Not only has greater simplicity been achieved; it is now possible to build these engines in far larger units than hitherto. In 1897, when the first successful engine was constructed, the maximum unit output was 20 brake horse-power. In 1911 engines of 1,000 brake horse-power were being constructed. Still further progress was made by 1917, when 12,000 brake horse-power in one unit was reached. To-day one of the largest Diesels in the world is a nine-cylinder double-acting two-stroke engine of 15,000 brake horse-power installed at the Hamburg Electricity Works.

Most large Diesel engines are now constructed on the double-acting, two-stroke principle. The older single acting four-stroke type has not yet been made economically in large sizes. Double-acting, four-stroke engines can be made in sizes up to 10,000 brake horse-power, whereas even with the 15,000 brake horse-power engine at Hamburg the limit of size in double-acting two-stroke engines has not yet been reached.

Higher piston speeds than used formerly are now adopted. Scavenging air for clearing out exhaust gases which would otherwise linger in the cylinders is introduced through ports in the cylinder wall, other ports being provided for the exit of the gases and air. These ports are opened and closed by the movement of the pistons, as indicated when describing the hot bulb engine. The output of Diesel engines, whether four- or two-stroke, can be increased by adopting what is known as "super-charging." This implies an increase in pressure, obtained by arranging for the exhaust valves or ports to be closed before the pre-compressed air for scavenging has ceased to enter the cylinder. In this way a higher initial pressure is achieved, whilst maximum and mean temperatures can be lowered. The result is to increase the output of the engine, and at the same time the fuel consumption is reduced.

We have referred to airless injection engines built on Diesel lines. It is only in the last few years that this development has taken place. As might be imagined, it leads to much simpler construction. Beyond the usual engine parts, such as cylinders, pistons, connecting rods, crank shafts, etc., there is practically nothing but a fuel pump, the compressed air starting device, cooling system, and a small blower for supplying the air for scavenging purposes. Starting from cold an engine of this type can be run up to full speed and load in a few minutes. It is instructive to compare such an engine with a steam turbine plant of equal capacity. With the turbine we must, of course, include the boiler, the condenser, and a large number of accessories. So far as rapid acceleration to full load conditions is concerned, there is, of course, no comparison. The steam plant is left a long way behind. These considerations, together with higher thermal efficiency, have in recent years given a great impetus to the manufacture of Diesel engines.[1] From day to day countless experiments are being made. Men test fuels in laboratories, other men make calculations or bend over drawing boards. Others, again, are busy constructing engines to new designs or carrying out tests on the latest products of the workshops. The result is, in the long run, an ever-decreasing complexity of construction and operation, combined with greater efficiency and reliability, and normally, lower first cost.

If in thirty-five years an entirely new type of engine has been evolved, modified, and improved almost out of recognition, and if in the same period this offspring of Rudolf Diesel's brain has grown in size from 20 to 15,000 brake horse-power, who will venture to say what may or may not be possible in the production of Diesel engines thirty-five years hence ?

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[1] Owing to developments in recent years involving combinations of the Diesel with the " airless injection " principle referred to in the previous section (which, as there noted, is English in its origins) it becomes increasingly difficult to justify the retention of the name " Diesel " in this connection. It is rather as though we were to refer to all steam turbines as " Parsons " engines. Nevertheless, the name is convenient, and for that reason has been retained here. The Diesel Engine Manufacturers' Association defines a " Diesel " engine as " An internal-combustion engine in which the fuel, injected after compression is practically completed, is ignited solely by the heat resulting from the compression of the air supplied for combustion."

(Courtesy of Messrs. the Daimler C

Gottlieb Daimler, 1834–1900.

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4

Volatile Spirit Engines

The automobile and the motor bicycle have made volatile spirit engines almost universally familiar. This section will accordingly be very brief, recording little more than a few salient facts without which our outline of internal combustion engine design would be incomplete.

Modern spirit engines can be traced back through direct descent to the patent taken out by Gottlieb Daimler in 1885. The engine which he made and fitted to a bicycle in 1886 was designed to run on gas or petroleum vapour and air. It was constructed to work on the Otto or four-stroke cycle like the other internal combustion engines of that time. A later design which followed in 1889 was a considerable improvement over his first effort, and the engine was thereupon experimented with for propelling vehicles. Carl Benz, of Mannheim, had also produced a small engine in 1885, while between 1887 and 1890 an Englishman, Butler, designed an engine to work on benzoline spray ; the ignition being at first effected by means of a Wimshurst machine. Following these initial essays a number of French engineers undertook the exploitation of spirit engines for propelling vehicles, among the best known of the pioneers being Panhard, Levassor, Peugeot, De Dion, Bouton, and Delahaye.

Modern engines of this type are usually single acting, and may work on either the four-stroke or the two-stroke cycle. The fuel used is either petroleum spirit, benzol, or alcohol ; or it may be a mixture of two or more of these fuels. The number of cylinders is only limited by practical considerations. Either the crankshaft rotates, or the cylinders may rotate about a fixed crankshaft, as in some types of aeroplane engines.[1]

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[1] The first radial type aeroplane engine was built by Charles Manly in 1902 for Professor Langley's " Aerodrome," and is now in the Smithsonian Institution.

" When we consider that the most popular type of airplane engine of to-day is almost identical in its general detail and arrangement with the one evolved by Charles Manly in 1902, we are lost in admiration for a man who, with no data at his disposal, no examples of similar art on which to roughly base his design, and no workmen capable of making the more difficult parts of his engine, nevertheless, through the processes of a logical mind, the intelligent application of the science

Cooling may be either by water-jacket or air. Lubrication is usually by oil distributed through pipes and ducts under pressure, on the system originally invented by A. C. Pain and adopted for high speed steam engines. Valves are normally of the mushroom type, but in some engines are made on the " sleeve principle "—that is, the piston travels within a movable liner, the movement of which opens and closes inlet and exhaust ports. No vaporiser is required, the spirit volatilising at all ordinary temperatures in a vessel called a carburettor. The liquid issuing from a jet is broken up into a fine spray by an inrush of air, forming an explosive mixture readily ignited by an electric spark. Both vapour and air are drawn into the cylinder and compressed, so that there is a temperature limit to the degree of compression which can be adopted. Electric ignition is now universally used, the mixture being fired by a spark passing between the points of a spark plug. Owing to a tax graduated according to horse-power a relatively small, compact, high-speed engine has been evolved in Great Britain for propelling the less expensive types of motor cars.

Spirit engines have been developed to meet a variety of needs. Besides the propulsion of cars, motor-boats, and aircraft, they are used for country house electric lighting sets, also for industrial purposes where a light, handy, portable unit is required. Thus they may be used for driving concrete-mixers, working temporary hoists, driving air compressors, and in general supplying power in connection with structural engineering work. But here they are in competition with engines running on cheaper fuels, and sometimes with electric motors. For electric lighting the speed is controlled by a governor, but when used for propulsion purposes the engine must be capable of giving an even turning effort over a wide range of speed—that is, it must have what is commonly called flexibility.

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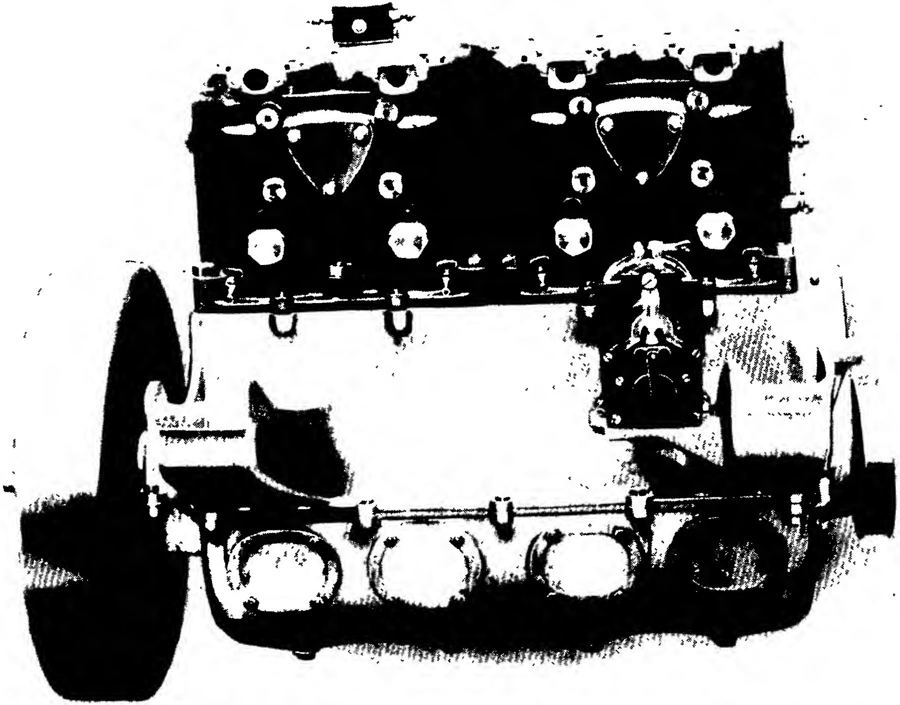
of mathematics, and the use of his surprising mechanical skill, succeeded in constructing an engine developing 52·4 horse-power for a weight of 125 lbs., or a weight of 2·4 lbs. per horse-power, which stood up under severe tests, once even going through a full power, non-stop run of ten hours."—C. L. Lawrance, M.A.S.M.E.



[Courtesy of Messrs. the Daimler Co., Ltd.

The first sleeve valve engine, 1909. C. Y. Knight's patents.

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The modern volatile spirit engine affords an excellent illustration of what may be done by the application of science to design and processes of manufacture. As might be expected, the quest for higher efficiency is responsible for a great deal of valuable research work. A good example of this is provided by the development of the aluminium piston. It has been known for some years that cast iron pistons get appreciably hotter than aluminium pistons of equal size. This means, of course, that aluminium is a better conductor of heat, a fact of considerable importance so far as internal combustion engine design is concerned. But it was not until investigations were carried out on scientific lines that any reliable particulars of relative efficiencies were available. Experimenting with pistons of 100 millimetre diameter, Professor A. H. Gibson, of Manchester University, found that at medium compression ratios a cast iron piston of normal design develops about 6 per cent. less power than its equivalent in aluminium, whilst requiring about 8 per cent. more petrol per brake horse-power.

In few details has greater advance been made than in the ignition system. Electric ignition was experimented with at an early date, but was abandoned as being altogether too unreliable, a platinum tube heated by a petrol lamp being the arrangement commonly adopted. Now there are several highly efficient forms of electric ignition apparatus on the market, each of which works in conjunction with an ordinary spark plug. We speak of an " ordinary " spark plug, but this seemingly commonplace article would be far more accurately described as extraordinary. Spark plugs are now universally expected to be capable of passing a spark across a gap of from fifteen hundredths to twenty-five hundredths of an inch under a gas pressure of 80 lbs. to the square inch. They must also supply a spark at any speed from about 100 to 4,000 r.p.m. In a six-cylinder automobile engine running at 3,000 r.p.m., well over half a million explosions take place—each in a tiny fraction of a second—in an hour's run when travelling at an average speed, say, of thirty miles an hour.

CHAPTER IV

WATER POWER PLANT

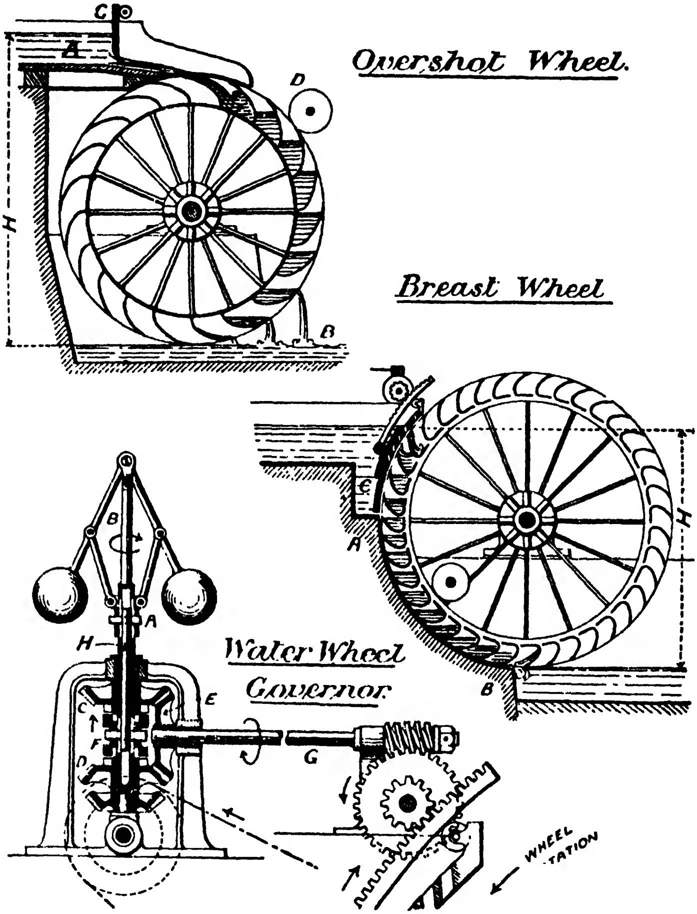
I

Water Power Pioneers

We shall now leave heat engines for a while, and turn to another field of human endeavour in which engineers are busily " directing the sources of power in Nature for the use and convenience of man." Already in an earlier chapter we have told how man relied for power largely upon simple water wheels for many centuries. Several types were used, some with a vertical, some with a horizontal axis. It is impossible to decide from the evidence available which came first. Since the water-raising wheel with a horizontal axis appears to have been known in the time of the Sumerians, and is described in Roman times by Vitruvius, who also describes the water-power wheel with horizontal axis, it seems reasonable to suppose that this type of wheel was evolved at least as early as any other. Contrary to the conclusions of Bennett and Elton in the *History of Corn Milling*, there is no evidence whatever that the earliest water wheels were on a vertical axis, though of course this *may* have been so. We have given elsewhere our reasons for concluding that the water wheel mentioned by Pliny was also on a horizontal axis, operating pestles by a trip action similar to that indicated by Heron of Alexandria for his windmill, and as still used for corn milling and rice husking in various parts of the world.

There are three main types of water wheel with horizontal axis. One of these is designed for the water to pass over the wheel ; the others for water to pass under it. Hence the names " overshot " and " undershot " by which they are known. Of the latter a variety called the " breast wheel " is an advance on the ordinary undershot arrangement.

The overshot wheel may be termed a gravity machine, so also may the breast wheel. Each depends on the weight of water descending in its buckets, though the overshot wheel also receives a small portion of its power from the water striking the buckets on entry. In the breast wheel the buckets are so shaped, and are so closed in by masonry, that water is retained


Overshot Wheel.
C
A
D
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Breast Wheel
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Water Wheel Governor
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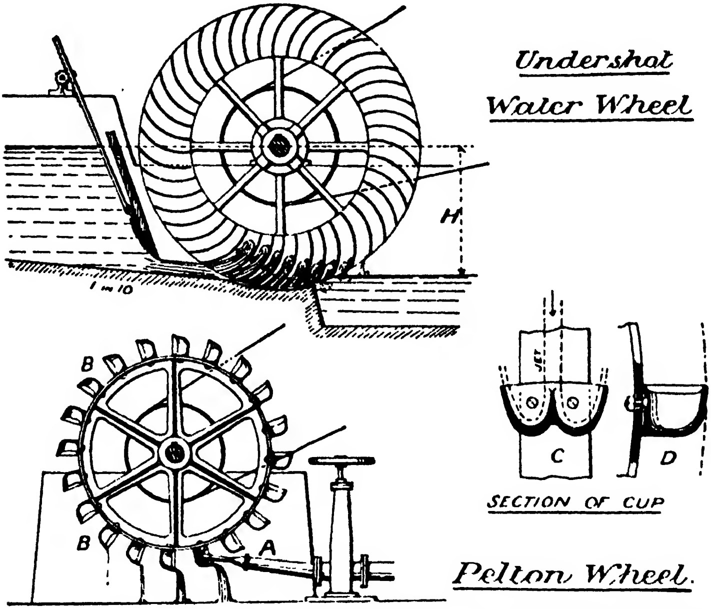
WHEEL ROTATION

(From Lineham's *Text-book of Mechanical Engineering.*)

Types of water-wheel.

in them as long as possible while they are descending. The simpler kind of undershot wheel depended in its earlier form upon the impulse due to the flow of a river acting on flat paddles at the rim. This wheel was very inefficient, though useful for tidal rivers subject to changes of current between ebb and flood. Its efficiency was increased by building a dam across the river and leading a large part of the water down a mill race, where, rushing through a narrow channel, it was compelled to act on the paddles of the wheel to greater effect.



(From Lineham's *Text-book of Mechanical Engineering.*)

Poncelet and Pelton wheels.

But a defect in this arrangement was that if the wheel was designed to work at high speed, then the water, being discharged at the speed of the wheel itself, carried with it much energy which should have been received by the wheel. And if, on the other hand, the paddles moved slower than the water swirling through the channel, then there was a loss of energy through impact. Smeaton made elaborate experiments on both overshot and undershot wheels, as recorded in his *Experimental Enquiry;* but it was L. N. M. Carnot, father of Sadi Carnot, who first clearly enunciated, in 1787, the proposition that for maximum efficiency in a water engine the fluid must enter it without impact and leave it without energy. J. V. Poncelet designed an undershot wheel in 1824 which very nearly met these requirements. He fitted his wheel with curved paddles or blades; while the water channel was narrowed to fit closely to the wheel. The approaching water first ran smoothly up the blades and then as smoothly back again, leaving them, finally, without motion relative to the earth, having parted with most of its kinetic energy to the wheel. This was a definite step towards the impulse water turbine.

Meanwhile the simple horizontal wheel on a vertical axis had been considerably improved. Illustrations begin to appear about the end of the 15th century of such wheels with inclined and sometimes curved vanes, upon which a jet of water impinges after issuing from a nozzle or conduit.

Leonardo da Vinci, who from an engineering point of view was perhaps a compiler of existing ideas rather than an original inventor,[1] gives such an illustration in one of his notebooks. A further development is shown by Besson in his posthumous work *Theatrum instrumentorum et machinarum*, published in 1578. A similar wheel to Besson's is given in Belidor's *Architecture Hydraulique*, 1737.

Still another development was a reaction wheel on a vertical axis, similar in action to Heron's steam eolipile, which was proposed by Robert Barker and constructed by Desaguliers about 1743. This idea is still utilised on a small scale in a neat form of lawn sprinkler with which the reader is no doubt familiar.

At this point it will be convenient to quote the following definition: " A turbine is a rotary engine in which power is derived from the pressure of a fluid on the sides of channels in the rotating part, which channels the fluid traverses in one direction only, approaching the rotor with velocity in the direction of rotation, and leaving it wholly or partly deprived of that velocity." Where water enters a wheel without pressure, we have an impulse turbine. Where it enters under pressure, either with or without velocity relative to the wheel, we have a reaction turbine.

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[1] But see *The Mechanical Investigations of Leonardo da Vinci*, by Ivor B. Hart (Chapman and Hall).

Now, just as Poncelet's wheel may be considered the prototype of the impulse turbine, so Barker's mill may be considered the prototype of the reaction turbine; though neither one nor the other is itself a turbine if the foregoing definition be accepted. As for the word "turbine" itself, this was apparently first used by Burdin in 1828 to describe a machine which he had designed in 1824. Though in principle similar to Barker's mill, this turbine of Burdin's incorporated the improvement that water entered the rotating part with an initial angular velocity, and left it without velocity.

Burdin played an important part in water-turbine development at this time. In his course of instruction at the St. Etienne technical school, he dealt with various aspects of water-power engineering. Among those who had benefited by this instruction was Benoit Fourneyron, and between 1823 and 1827 Fourneyron constructed a turbine which was a vast improvement upon anything that had previously been designed. By 1832 he had built a turbine developing 50 horse-power, and described his invention in a paper submitted to the Society for Industrial Encouragement, Paris, 1834. This Society had, in 1823, offered a prize of 6,000 francs for a commercially useful improvement upon turbine-like wheels described by Belidor, and the prize was awarded to Fourneyron on the strength of his achievement.

The moving part or runner of Fourneyron's turbine was in some respects not unlike Poncelet's wheel placed on a vertical axis. There, however, all resemblance ends. In the Poncelet wheel the water had only one point of entry and departure; that is, at the periphery of the wheel. In the Fourneyron turbine, the water entered the moving vanes from a fixed cylinder inside, and left them at the periphery of the wheel. For this reason it is known as an "outward flow" turbine. The central fixed cylinder was itself fitted with guides to lead the water into the spaces between the moving vanes.

In 1837 the Jonval turbine appeared. In this the blades and guides were set round cylindrical drums. The water flowed in a direction parallel with the axis of rotation, hence machines of this type are often known as axial or parallel flow machines. The upper wheel with fixed guides is a reversed duplicate of the rotating wheel with its curved blades.

The first radially "inward-flow" turbine (so called to distinguish it from outward-flow machines like Fourneyron's) was designed by S. B. Howd, an American engineer, in 1838. It was later considerably modified by another American, J. B. Francis, of Lowell, Mass, who designed an improved form in 1849. The rotating wheel is in this type within the fixed guide blades, which form part of an annulus surrounding the wheel. It is therefore smaller and more compact than in the Fourneyron turbine. This in effect meant that the latter (even though more efficient) was structurally at a disadvantage, requiring a larger and more expensive wheel for a given power, and operating at a lower speed.

In 1856 Girard effected improvements in the Fourneyron turbine. Girard's machine, which was of the impulse type, will be referred to again later. Here we must make brief reference to the evolution of the more familiar type of impulse turbine known as the Pelton wheel.[1] The reader will remember that in the Poncelet wheel, the water entered and left the blades at the same point. In consequence the Poncelet wheel could only be used for very low falls, since even a moderate head would result in the water running so far up the blades that energy would be lost in impact against the drum. In 1856 Cheetham remedied this defect by designing blades formed like double buckets, with a centre ridge upon which the water at entry impinged. Improvements in the shape of the buckets were effected by Pelton in America, to whom a patent was granted in 1880. He also arranged for the incoming stream of water to be concentrated into a single jet by passing through a nozzle of suitable proportions. The jet of water, impinging on the ridges of the buckets, was divided by them into two streams. Had the wheel been fixed, these streams would have left the buckets in a direction almost opposite to that of entry. The difference between this " apparent " path of the water and its true path will be indicated in the next section. Here it will suffice to say that with Pelton's improvements the transition from water wheel to impulse water turbine was complete.

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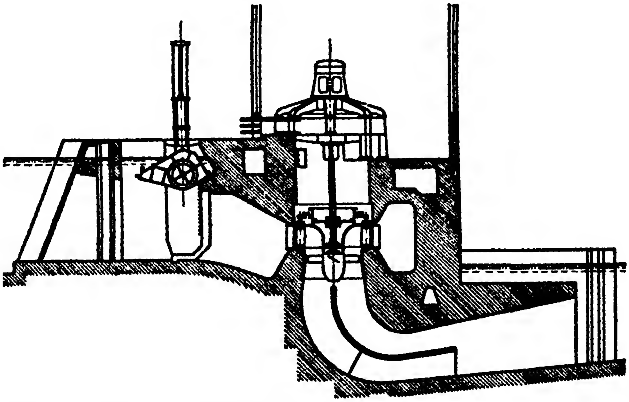
[1] An American authority states that the Pelton wheel has been developed from the crude wheels first used in California under fairly high heads as early as 1854, and known locally as "hurdy gurdy" wheels. See *Water Power Engineering*, by H. K. Barrows, p. 195.

2

Types of Modern Water Turbines

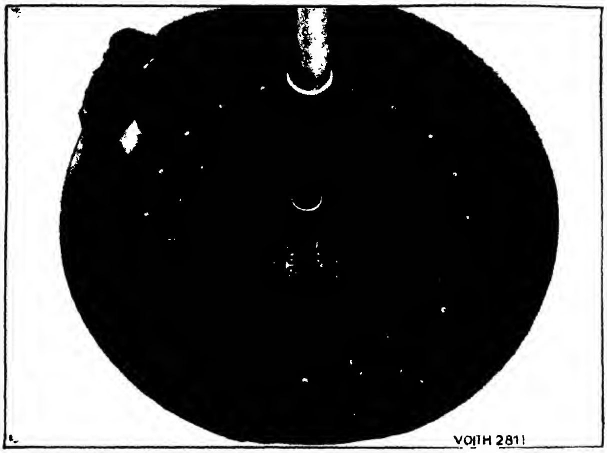
All modern water turbines have evolved out of one or another of the types discussed in the previous section. They are usually classified as " impulse " or " reaction," like steam turbines ; the reaction class being subdivided into inward-flow, outward-flow, axial-flow, and mixed-flow, according to the direction followed by the water between the inlet and outlet of the runner, as the rotating part is now generally termed.



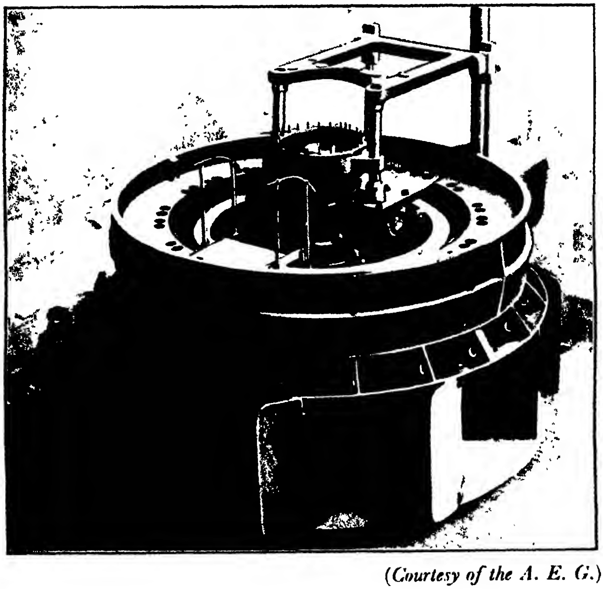
Section through inward-flow water turbine pit (*A.E.G.*)

Sometimes there is difficulty in understanding the precise significance of the words " impulse " and " reaction " as applied to water turbines. The nature of an impulse is fairly obvious, but what takes place in a reaction turbine is not so self-evident. We therefore make no apology for discussing the matter in greater detail. The essential difference between the two classes is that impulse turbines, as already indicated, operate with water at atmospheric pressure only ; the water, moving at high velocity, transmitting its kinetic energy to the buckets upon which it impinges ; while reaction turbines rely partly upon water pressure and partly upon energy of motion. The runner and guides of a reaction turbine are completely filled with water and so the machine operates at a pressure higher than that of the atmosphere, not only in guides and runner passages but also in the clearance space between runner and guides. The runner gains in energy as the water loses pressure and "absolute" velocity while flowing through it. Motion is due to the reaction taking place as the water leaves the wheel passages. This can be seen more clearly if we consider the little lawn sprinkler to which reference has already been made. Here motion is readily seen to be due to the jets of water issuing from the two nozzles. Suppose now that we have several nozzles instead of only two ; and let us assume that the central chamber is fixed instead of revolving with the nozzles, the latter only revolving. Then we shall get a crude form of outward-flow reaction wheel without guide blades. This wheel would be inefficient ; as, in consequence of the whirling motion, the water would leave the nozzles at too high a velocity. By means of fixed guide blades curving in the direction of motion, Fourneyron gave the water an initial whirl in the opposite direction. This increased the efficiency by reducing the velocity of whirl at which the water left the nozzles—or runner vanes, as they were in his machine.

In the original Francis inward-flow turbine the water was turned to flow away axially after discharge. The wheel was relatively large, and ran at a low speed. But water turbine designers, like the designers of other types of prime movers, have constantly sought after higher speeds. High rotational speed is especially desirable in hydro-electric plant, if it can be obtained without loss of efficiency. Wheels and generators



Bird's-eye view of inward-flow water turbine.



(*Courtesy of the A. E. G.*)

man is standing by

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established by Eytelwein in 1801.[1] This follows directly from Carnot's proposition that the water should leave the wheel without energy ; that is, without velocity relative to the earth. A very simple calculation will make this clear. Consider, for example, a jet impinging on a bucket at 200 feet a second, and being deflected by the bucket into the opposite direction without frictional or other losses. Then, if the bucket did not move, the water should return with a velocity relative to the earth—and the bucket—of 200 feet a second. But if the bucket moves away from the jet at half-speed, that is, at 100 feet a second, then the jet will be turned back with a speed *relative to the bucket* also of 100 feet a second. The bucket going one way, and the jet leaving it at an equal speed in the opposite direction, it will be obvious that the water leaves the bucket (in a theoretically perfect turbine) with no velocity relative to the earth.

We have in this example a wheel with buckets travelling at a linear speed of 100 feet a second. If the wheel is, say, 16 feet diameter across the centres of the buckets, the length of the circumference will be about 50 feet. That is, each bucket (and with it, of course, the wheel) will make approximately two revolutions a second, or 120 r.p.m., which is quite a low rotational speed. These figures are for illustrative convenience only. In actual practice a higher rotational speed would be adopted, with a proportionally smaller and cheaper wheel. In actual practice, also, it is found that maximum efficiency is obtained when the velocity of the impinging water jet is a little more than twice that of the buckets.

The original Pelton buckets were defective, being made with an outer lip at the point first struck by the jet of water as the bucket entered its path. On striking this lip the direction of the water was abruptly changed, energy being dissipated through eddying ; and, in addition, the water on leaving the bucket struck the back of the next bucket, causing loss due to back pressure. An improvement was made by Doble, of San Francisco, who cut away the outer lip, and obtained higher efficiency in consequence.

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[1] Eytelwein, *Handbuch der Mechanik und der Hydraulik.*

Usually only one nozzle is used, the use of two being accompanied by loss of efficiency due to interference of the jets.

In Europe an outward-flow impulse machine has been developed from Girard's designs, and is still known by his name. This at first sight looks like a reaction turbine. But Girard ventilated his wheel passages and also widened them towards the outlet so as to relieve the water of all pressure above that of the atmosphere. The energy obtained under these circumstances is due to velocity, which puts this turbine in the impulse class. Impulse turbines, as already stated, are suitable for relatively high heads, about 3,000 feet being so far the limit of head utilised in America, while a head of over 5,400 feet has been utilised in Europe.

3

Methods of Speed Control

To make any prime mover run steadily there must be a continuous adjustment of the energy producing rotation to the work which has to be done. In a reaction water turbine the quantity of water entering the guides may be altered by a cylindrical shroud which, fitting over the outside, is raised or lowered to give greater or less access to the guides. This arrangement, however, is inefficient. At any position less than " full gate " as it is called, there is a sudden contraction of water, followed by sudden expansion, leading to energy losses through eddying and cavitation and loss of pressure at admission. Modern reaction turbines are therefore usually made with movable guide blades, the blades swivelling and acting not only as guides, but also as wicket control gates. Sometimes separate gates are used. As these move they widen or contract the spaces between them. In the propeller type turbine designed by Professor Kaplan of the German Technical University Brünn, the blades on the runner move also to ensure the highest possible efficiency for all gate positions.

Speed control on a Pelton type turbine is effected in two ways. The jet may be deflected so that only a portion of it strikes the buckets, or the jet itself may be reduced by an arrangement consisting of a rod, pointed like a pencil, which is moved forward into the nozzle from inside. As with all other prime movers it is very necessary that such adjustments, both on impulse and reaction turbines, should be made automatically. This can be done by using a centrifugal governor.

Every reader will be familiar with the mechanism on an engine for effecting speed control. Pivoted weights rotate about a shaft driven by the engine. Their freedom of movement is opposed either by gravity or, more usually, by springs. If there is a change in the engine speed the balance between the centrifugal force tending to move the weights outward, and the tension on the springs tending to pull them in, is upset. A margin of energy is then available to open or close a valve which is linked up to the arms from which the rotating weights are suspended. Mechanically there are many variations on this simple arrangement, but they are all much the same in principle.[1]

The energy available in an ordinary governor is not sufficient, however, to operate the heavy speed control mechanism of large water turbines—particularly having regard to the weight of water and its high degree of incompressibility. The energy of the governor is therefore used to operate a small valve controlling a flow of oil under pressure through a pipe. The pressure may be anything from 150–200 lbs. to the square inch. From the pipe the oil flows to a small cylinder containing a piston which is connected mechanically to the turbine gates or jet control device, as the case may be. The oil supply is taken from a reservoir, pressure being maintained by power taken from the turbine itself. A receiving reservoir is also required to hold the oil returned from the discharge side of the regulating piston until it is pumped back into the pressure reservoir. This, it should be added, is one of many similar arrangements adopted in actual practice. Sometimes water is used instead of oil. It will be seen that, whatever the details, all governing mechanisms depend upon change of speed, however small, to bring about the necessary regulation, and with it a return to normal speed conditions. In addition to the main operating parts, most modern water turbine speed-control mechanisms include some means of varying the speed above or below normal by a predetermined number of revolutions. An emergency governing device is also almost invariably included. At a speed beyond which it is considered unsafe to run the turbine a " trip " or trigger is released by the action of the fly-ball governor. This holds the oil relay valve in a position which brings the turbine to a standstill. The trigger must then be replaced by hand before the turbine can be run up to speed again. Another emergency device consists of a solenoid energised from the switchboard in hydro-electric power stations. This solenoid also acts on the oil relay valve, enabling the switchboard attendant to stop the turbine promptly if he considers for any reason that it is necessary to do so.

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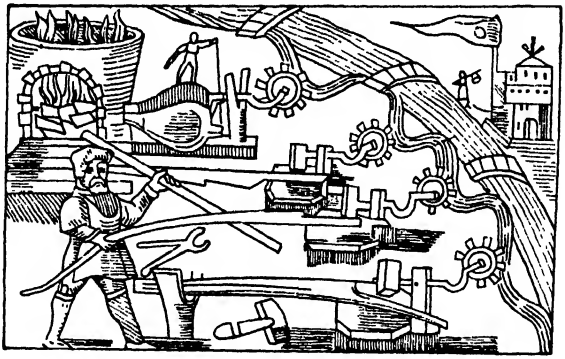
[1] James Watt developed the centrifugal governor and applied it to his steam engine. A similar device, however, called a "lift-tenter," had been invented long before his time, and adopted in corn-mills for varying the pressure between the mill-stones to compensate for changes in velocity of rotation.

From these devices it is only a step to remote control, and even to fully automatic water-power plant. When a turbine is installed at some distance from the main power station it is very desirable to avoid duplication of staff. Under these circumstances men can be replaced by switchgear. The methods adopted involve principles similar to those on which automatic telephones are based. To discuss this matter in detail would take us too far afield, but it may be stated that hydro-electric units can frequently be started up and stopped from a distance quite readily by means of push-button control. Full automatic control can be secured by the use of floats which, operating a switch controlling an electric solenoid, stop the plant when the head-water level falls below a point at which it would be inadvisable to keep the turbine running. So long as it is in operation the turbine speed is, of course, controlled by the governor in the ordinary way.

In the progress which has been made with speed control and the beginnings of automatic operation we catch a glimpse of the most far-reaching possibilities of further development. The example we have given here illustrates a general trend throughout the whole field of mechanical and electrical engineering. There can be little doubt that much machinery which at present necessitates close supervision will in the near future be fitted with self-regulating devices—a feature of the quest for power that is bound to react extensively on the work-a-day lives of men the world over. We believe that in the long run such developments are bound to be beneficial ; but—as some cynic has remarked—" in the long run we are all dead." It is to be hoped that all who are concerned with human welfare will give earnest consideration to the employment problems which must inevitably be faced *in the short run*, following upon any extensive replacement of men by automatically controlled power-driven machinery.



CHAPTER V

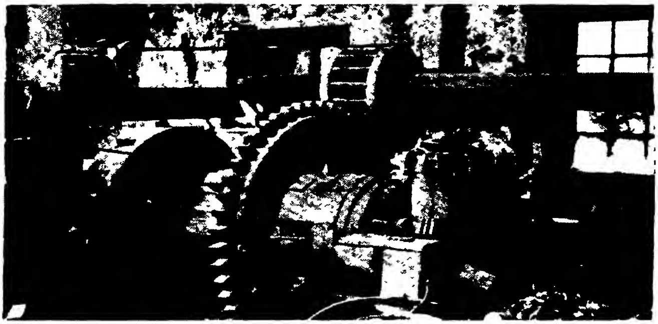
MECHANICAL TRANSMISSION OF POWER

I

Some Primitive Transmission Gears

We have now seen how man secures an ever-increasing direction and control of the energy resources of Nature; effecting, by the application of science to the construction of power plant, an almost incalculable increase in his capacity for getting work done. But no matter what the scale, it is no use producing power if it cannot be conveniently applied. And as power can seldom be applied directly to work—as it is, for example, in the Humphrey gas pump—some form of transmission must almost invariably be adopted. The long-distance transmission of power or, alternatively, the transportation of materials from which power is derived, is taken for granted nowadays. But in earlier times it was exceedingly rare to transmit it more than a few feet at most. So it came about that before our modern transmission methods were elaborated, the application of power was necessarily very closely associated with its production.

At what stage in his history man developed a system of linkages and levers out of the simple lever, and toothed wheels out of ordinary wheels, it is impossible to say. Certainly these were among the earliest means adopted for the transmission of power. The cord used for producing rotary motion, as in the bow drill and fire-kindling apparatus, must also have been applied to other uses at an early date. The simple pulley-and-rope combination was known to the Assyrians. Among early writers Heron gives examples of levers, linkages, and toothed wheels. We have already noted that Vitruvius mentions the transmission of power by toothed wheels in connection with water-operated mills. Crude as they were, many



(*Courtesy of Messrs. Edgar Allen & Co., Ltd.*)

18th century gearing for water-operated tilt hammer, Hay Creek Forge, Berks County, U.S.A.

(*Courtesy of the Newcomen Society.*)

18th century brake-wheel and trundle for windmill, South Yarmouth, U.S.A.

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enturies passed without material improvement upon these imple appliances being effected. Toothed wheels of the 4th century may be seen in a large clock mechanism, formerly at Wells Cathedral but now in the Science Museum, London. A better general idea of early achievement in transmission gearing may be gathered from Agricola's *De Re Metallica*, published in 1556 and translated in 1912 by Herbert Hoover and L. H. Hoover. Here we find quaint-looking cog-wheels, pinions, axles, rods, levers, and links in profusion. Nearly everything was made of wood, with bits of metal attached here and there for the wearing parts.

No great progress appears to have been made even when we come down to the early part of the 18th century, if we may judge by reference to illustrations from works such as Diderot's *Encyclopédie*, and *L'Art de L'Épinglier* by de Réaumur. New ideas are conspicuous only by their absence. Men's notions of mechanical principle were, indeed, so vague, so completely dominated by rule of thumb procedure, that very little further advancement was possible until the coming of steam brought novel incentives, and the increase of scientific knowledge facilitated the production of greatly improved devices to meet new and urgent demands for the efficient transmission of power.

2

Modern Rotary Gearing

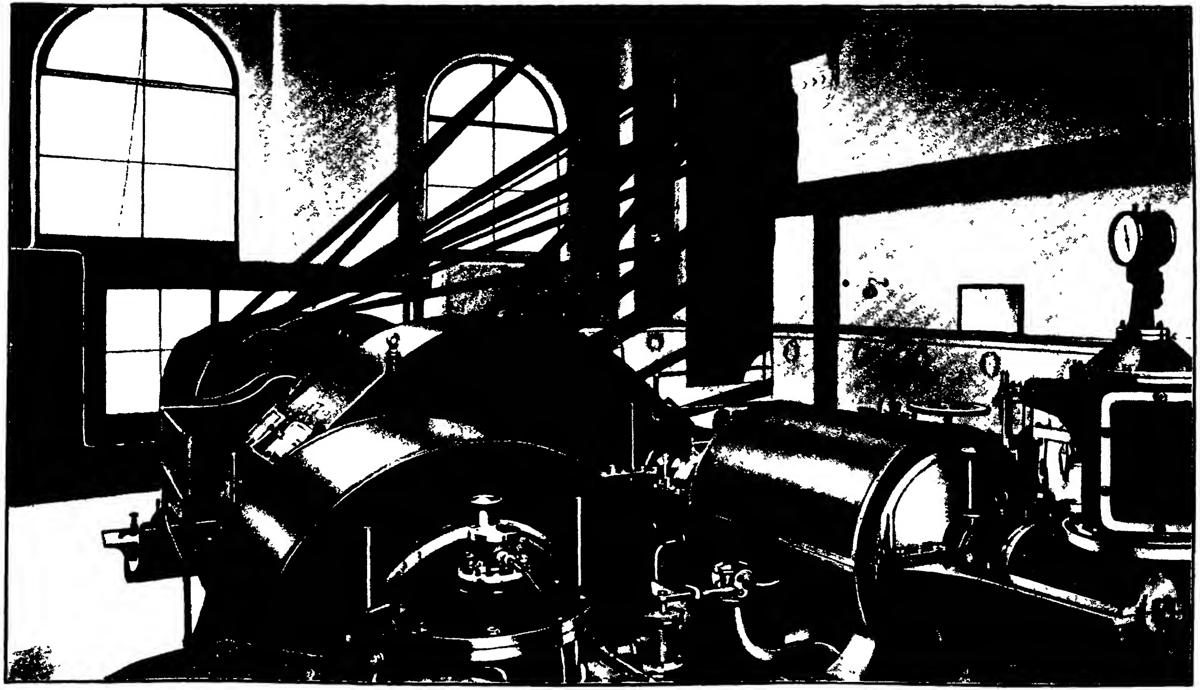
There are many systems of transmitting power which involve rotary motion, but one idea has in recent decades played a decisive part in the evolution of them all. Power is a product of force and velocity, so that for a given horse power to be transmitted, force may be decreased as velocity is increased. Other factors affecting efficiency remaining unchanged, it follows that there must be considerable advantage in running transmission gear at the highest practicable speed. Dimensions and weights can be reduced, there will be less pressure on bearings, less friction, less wear and tear. In practice, as we shall see presently, other factors do not remain unchanged.

There is for every type of transmission a limit of speed beyond which losses begin to outweigh the gains.

Belt gearing involves the use of belts, pulleys, shafts, and bearings. The belts are usually of leather, though various substitutes are now available as well. The leather is manufactured from cow and steer hides, the best quality being taken from the back of the animal and then tanned and curried. Tanning increases the strength, elasticity, and durability of the leather ; currying makes it soft and pliable. Everyone has seen leather belt transmission gear at some time or another, so that we need not describe it in detail. Apart from pioneer experimental work by Morin in 1834, and Briggs and Towne in 1868, the beginning of modern practice was the now classical paper on belt transmission read by F. W. Taylor in 1893 before the American Society of Mechanical Engineers. This provided the first rational basis both for current practice and for further research.

The reader will probably be aware that, even at its best, belt driving is an unsatisfactory form of transmission from a mechanical point of view. Nevertheless, it has a remarkable range of practical usefulness. It is relatively cheap, simple and adaptable, and so it has survived. Belt speeds are limited by the action of centrifugal force, which may either break the belt or stretch it and cause slip. At a speed of 3,000 feet a minute the loss due to centrifugal force is about 8 per cent. At 5,000 feet a minute this loss increases to about 23 per cent. In practice it is found that the most economical compromise is a belt speed of between 3,500-4,000 feet a minute, though, of course, individual transmissions must be adapted to meet special needs.

When power is transmitted by ropes running in grooves, higher speeds are permissible, since individual ropes are lighter than the leather belting used for drives transmitting equal horse-power, and are therefore less subject to the action of centrifugal force. Rope velocities of over 8,000 feet a minute have been successfully adopted. In Great Britain it is customary to use a number of separate, endless ropes, one running in each pair of grooves. In America one continuous rope is



(Courtesy of Messrs. William Kenyon & Sons, Ltd.)

Power transmission by rope drive from a steam turbine.

[To face p. 204.

(Courtesy of Messrs. Morse Chain Co., Ltd.)

450 brake horse-power chain drive to an alternator.

To face p. 205.

used, passing round all the grooves and finally over a small adjustable pulley used only for increasing the tension in the rope. Experts disagree about the relative merits of the two systems.

Wire ropes were introduced by Hirn in 1851. Being stronger but heavier and less flexible than cotton ropes, they are usually adopted for relatively slow-speed transmission over long distances. The economic range of this system is limited to about three miles. Wire-rope gearing has proved to be invaluable for such purposes as steam ploughing, hauling and elevating in collieries, operating funicular and cable tramways, ropeways, and boat towing on canals.

Various types of chain drive have been evolved. The most generally familiar is to be seen on all modern bicycles and many motor-cycles.[1] Another design, which has been increasingly adopted for general transmission purposes in recent years, is known as " silent " chain. It is a very beautiful piece of mechanism. For ordinary factory transmission, chains of the silent type should not normally be run at speeds over 1,500 feet a minute. They can be adapted to a wide range of requirements, and are used for transmitting anything from ¼ to 1,000 horse-power. One of the great advantages of all chain transmissions is that they are positive ; that is, there is no possibility of slip occurring, as with belts and ropes.

Spur wheels may be considered as a development out of one plain wheel driving another by frictional contact ; teeth having been added to prevent slip. The teeth are formed partly above and partly below the plain wheel circumference, which is then known as the pitch line and is used as a basis of reference in design. When shafts are not in the same straight line, bevel wheels may be used. Worm gearing gives a high velocity ratio and large mechanical advantage with a minimum number of parts. If the speed ratio is greater than 8 to 1, worm gearing is non-reversible.

One of the highest developments in rotary transmission engineering is the machine-cut double-helical gear. It was long ago observed that the smaller the pitch or spacing of the teeth the smoother two spur gear wheels ran together in mesh. That extraordinarily versatile genius, Robert Hooke (1635-1703), invented stepped gearing. This gave results similar to the smooth working of a pair of wheels with very fine spacing between the teeth. Now, it will be realised that if the steps are increased in number they will finally disappear, being replaced by what may be conveniently referred to as "lop-sided" teeth—what engineers call single-helical gearing. This is easier to mould or cut than stepped gear. But as it sets up an end pressure, the double-helical gear has now taken its place for steam-turbine and many other speed reduction and power transmission purposes. The loss of power in double-helical gearing can be kept down to 2 per cent.

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[1] There is an illustration of link chain, similar to that used on modern bicycles, in one of Leonardo da Vinci's notebooks. See F. M. Feldhaus, *Leonardo, der Techniker und Erfinder*, p. 81.

There are many other items of modern gearing which it would be interesting to examine, but we must pass on now to some of the highly important and interesting methods available for reducing friction in the types of gearing already discussed.

3

Reducing Friction [1]

Friction is a useful servant, but also a deadly enemy of power transmission. Wherever surfaces rub together, as in ordinary bearings, there friction does its best to convert energy of motion into heat. It is scarcely surprising, therefore, that vast industries now exist which have made it their sole business to assist in the great work of reducing undesirable friction.

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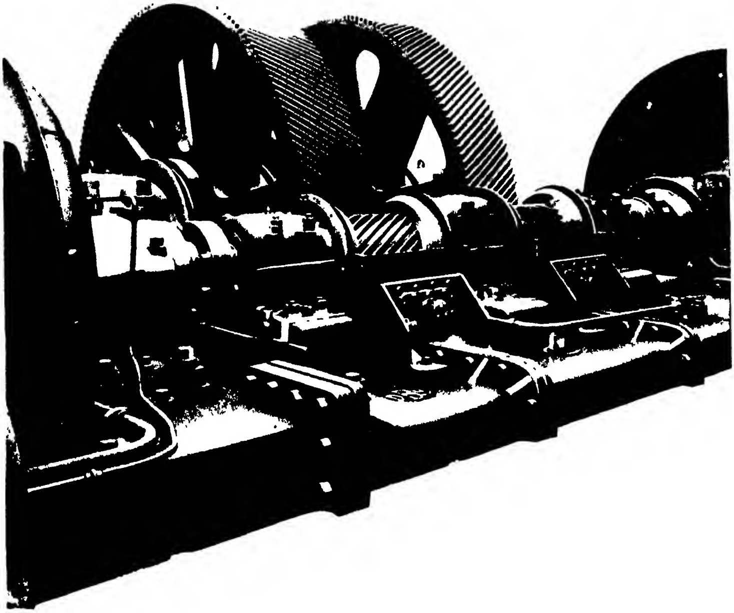
[1] In this section we have adopted the ordinary homely notion of friction being due to rubbing contact. As the late Lord Rayleigh remarked of fluid friction, rubbing contact is "a very convenient expression" to describe something we do not really understand. Actual contact between surfaces is, as a matter of fact, extremely improbable. It might be more scientific, perhaps, to say that while all things flow, some resist change of shape more than others; and further, that close proximity causing a tendency to change shape, a strain is set up which, when released by body deformation, is transformed into heat. There would appear to be a rapidly recurring sequence of strain, deformation, relaxation, heat . . . which tends to confirm the theory of heat being generated and emitted in quanta. But this does not account for the action of lubricants.



(*Courtesy of Messrs. David Brown & Sons, Ltd.*)

Modern double helical reduction gearing.

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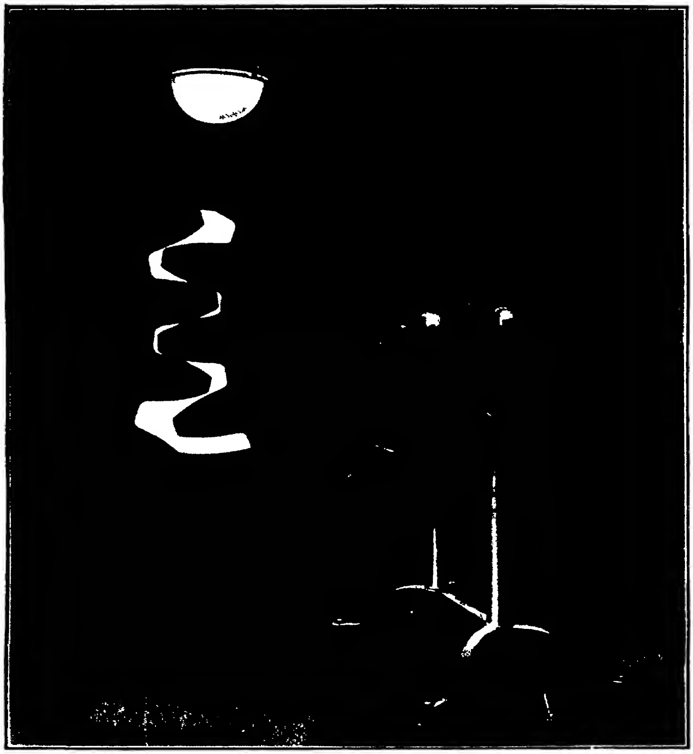

Courtesy of Messrs. David Brown & Sons, Ltd.

Optical projection of gear teeth.

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There is no theory which accounts for friction completely and satisfactorily. We can observe and record its effects with some degree of accuracy, however. We know, for example, that the greater the pressure between two dry surfaces, the greater will be the friction, due to one surface sliding over the other. We can also say that dry frictional resistance is not greatly affected by temperature, that it depends largely upon the nature of the materials in rubbing contact, that the friction of bodies at rest—the " sticktion," as it has been called—is greater than that of bodies in motion, and that when pressure between the surfaces becomes excessive, seizing occurs.

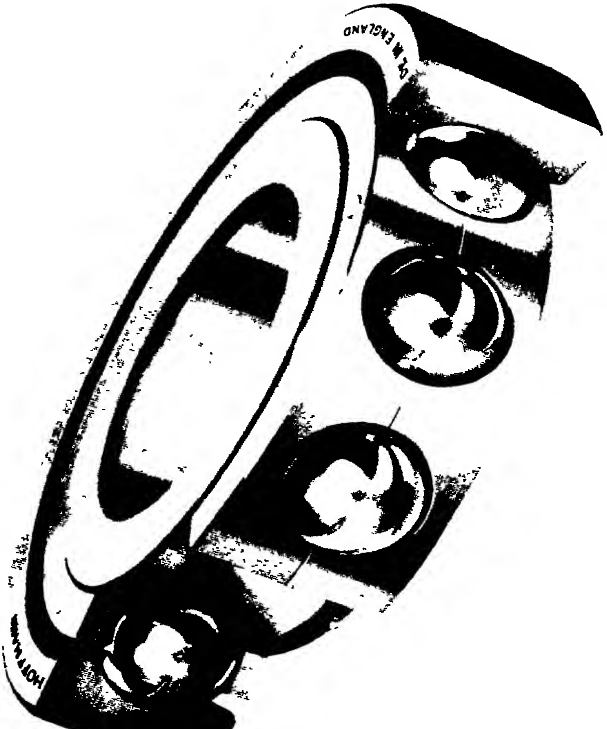
Now, as every reader is aware, friction can be reduced both by the use of suitable bearing metals, and by the use of lubricants. Various " anti-friction " mixtures of copper, tin, and lead, or copper, tin, and antimony, are often used. The harder constituents resist wear, while as a whole the alloy is sufficiently plastic to present a smooth, anti-friction surface to whatever other surfaces rub against it.

Without lubrication, however, friction is still excessive, and heat may be generated sufficient to melt soft alloys. Oil is therefore provided as well, and immediately a remarkable difference is noted. For the friction between the parts of a fluid is not sensibly increased by pressure at all, so that if the metal surfaces can be kept apart by oil, an increase of pressure will not increase the friction, as between dry surfaces. What happens then is that some of the oil adheres to the rotating shaft and travels with it, and some remains behind on the surface of the stationary bearing. One film of oil slides over the other. There is no longer any friction between the surfaces, but there is friction between the films of oil. Thick oil has greater viscosity, that is, it is subject to greater internal friction, than thin. As a general rule, therefore, the thinnest oil that will keep the surfaces apart should be used. We may note further that at high speeds the internal friction of fluids increases approximately as the square of the speed. This points to the use of a thinner oil at high than at low speeds.

In actual practice we get both fluid and solid friction. The losses in transmission are therefore heavy, not infrequently amounting to 25 or even 30 per cent. of the power to be transmitted. Yet most of this loss might be avoided by the use of ball or roller bearings. The principle underlying this type of bearing is the substitution of rolling contact for sliding friction. A ball rolling along a smooth surface may be regarded as rotating at each instant about that point in its circumference which is (for that instant) in contact with the surface. A perfectly round ball and a perfectly smooth surface can clearly be in contact only at one point at any one moment. There will therefore be no relative movement between the contacting points of the ball and the surface. In other words, there will under ideal conditions be no friction, and no need for any lubricant.

Now, the use of sliding friction bearings for transmission shafting can no more be justified, from a scientific point of view, than the use of sledge runners for transport with oil poured under the runners to reduce friction. In Book I we pointed out that the ancient Egyptians actually did transport heavy weights on sledges in front of which lubricants were poured by an attendant ; but that the Assyrians, on the other hand, used rollers for similar purposes, not oil ; and that the Sumerians were already using rollers and wheels before 3000 B.C.

Although the possibility of replacing sliding friction by rolling motion is thus seen to have been realised for at least fifty centuries, ball and roller bearings are—surprisingly enough—among the most recent of mechanical transmission developments. What appears to be one of the earliest references to anything approaching such devices occurs in the Memoirs of Benvenuto Cellini, written in the 16th century. The passage runs : " Having with the utmost diligence finished the beautiful statue of Jupiter . . . I placed it upon a wooden socle. . . . And within that socle I fixed four little globes of wood which were more than half hidden in their sockets and so admirably contrived that a little child could with the utmost ease move this statue." A definite description of a ball bearing is contained in a work published in London in 1772 : " Reflections upon Friction with a Plan of the new



(Courtesy of the Hoffmann Manufacturing Co., Ltd.)

Part section of a ball bearing.

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Machine for taking it off Wheel Carriages, Windlasses of Ships, etc., by C. Varlo, Esqr." This "machine" of Varlo's was very like the modern non-adjustable ball bearing, but was without the high-grade hardened steel tracks, ball-separating cage, and the precision of manufacture which give the modern product its extraordinary efficiency and wearing qualities.[1]

It was not until after 1880 that the first cup and cone type ball bearing was applied to the old-fashioned "ordinary" bicycle. Thereafter it was promptly adopted by all cycle makers of repute, and is therefore the type of ball bearing that is most widely known. It is entirely wrong in principle, the worst of its many defects being the wear of both balls and tracks, due primarily to a frictional spinning motion set up in the balls. To avoid this spinning action, standard ball bearings are now constructed so that all lines drawn through points of contact are at right angles to the axis of the bearing. Since the bearing is not completely filled with balls, a "cage" is fitted to prevent trouble due to the balls crowding together. The modern type of bearing being non-adjustable, defects due to inexpert adjustment are eliminated.

Ball bearings have been found by experiment to be quite unsuitable for heavy loads combined with shock or vibration. To meet the widespread demand for a more robust type the roller bearing was evolved. This is now made in its heaviest design to carry any load that a shaft is ever likely to be called upon to take. When used for transmission shafting it is possible to save 90 per cent. of the power absorbed in plain bearings. There is also a great saving in lubrication. Theoretically no lubricant at all is required. In practice the races are filled with grease, say once a year, not so much to provide lubrication as to keep out dirt and grit. The cage holding the balls requires a certain amount of lubrication, however, and this the grease provides.

It should be understood that ball and roller bearings are among the most carefully and accurately made of all engineering products, and should accordingly be treated with the respect due to the science and skill which such care and accuracy represent. Balls are made to guaranteed limits, both in diameter and sphericity, of plus and minus $\frac{1}{10000}$ of an inch. The successful operation of such bearings depends on accuracy in manufacture, quality of materials, care in erection, and freedom from grit and corrosion in operation. Given these conditions, they prove themselves to be one of the most useful adjuncts to the rotary transmission of power that engineering science has so far devised.

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[1] Leonardo da Vinci illustrates anti-friction rollers in his notebooks. See Usher's *History of Mechanical Inventions*, p. 188.

4

Fluid Transmission of Power

Air and water are the only fluid media which have been extensively used for the transmission of power. Compressed air has a long history behind it, reaching back through the devices of Heron and the wind guns of Ctesibius to ancient Egyptian times. But it was Denis Papin who, in 1653, first experimented with transmission of power to a distance by air pressure. Hoell, in 1775, noted the formation of ice when air was expanded after heavy compression. Medhurst, in 1799, compressed air to a pressure of 210 lbs. and transmitted it to a motor in a mine. The American engineer, Jacob Perkins, appears to have succeeded in liquefying air in 1826. The first really notable applications of compressed air, however, were made in connection with the Mont Cenis and St. Gothard tunnels in 1872 and 1873. Since that time progress has been rapid, both in Europe and America.

Mechanically, modern air compressors resemble steam engines in construction and appearance, or, if of the rotary type, steam turbines. The main difference in action is that, instead of a medium expanding and doing work, work is done upon and energy stored up in a medium by compressing it. Very often in a steam-operated reciprocating compressor the air cylinders are placed directly over the cylinders of what is otherwise an ordinary high-speed enclosed steam engine.

The design of compressed air machinery has been largely influenced by attempts to eliminate difficulties due to rise of temperature in the compressor ; and to cold produced by subsequent expansion in the motor, resulting in freezing of the exhaust ports when the air contains moisture. Early compressors were constructed so that the piston moved in water. The inertia of the water limited the piston speed, so spray injection at the end of the compression stroke was tried. This cooled the air, but caused lubrication difficulties, and eventually the modern water-jacketed compressor equipped with intercoolers between stages of compression was evolved. Turbo-compressors are now generally used where large capacity is required. Freezing trouble in the motors may be overcome by re-heating the air before entry, a practice which also greatly increases the efficiency of compressed air motors.

Compressed air has many advantages as a transmitter of power. Air can be obtained anywhere, compressed, distributed and freely discharged again after use. The first cost of power mains is not ordinarily very heavy, and the motors used are simple and easily kept in repair. Where there is danger of explosion, as in some coal mines, compressed air is widely used in preference to electricity, since not only is there immunity from danger due to sparking, but the air used is an aid to ventilation. The chief objection to this system is the low efficiency commonly obtained in practice. This is partly due to the inevitable loss of heat during transmission, and partly due to false economy in retaining a defective and overloaded pipe line. Additional motors are often added without making the necessary increases in the capacity of the transmission system. Moreover, it is not always possible to take advantage of reheating. Owing to these and other causes the overall efficiency of many compressed-air installations in British collieries is stated to be as low as 10 per cent.

Turning to hydraulic transmission, Simon Stevinus (1548–1620) is credited with having discovered the principle of the hydraulic press, while Blaise Pascal (1625–1662) clearly enunciated it in the following words :

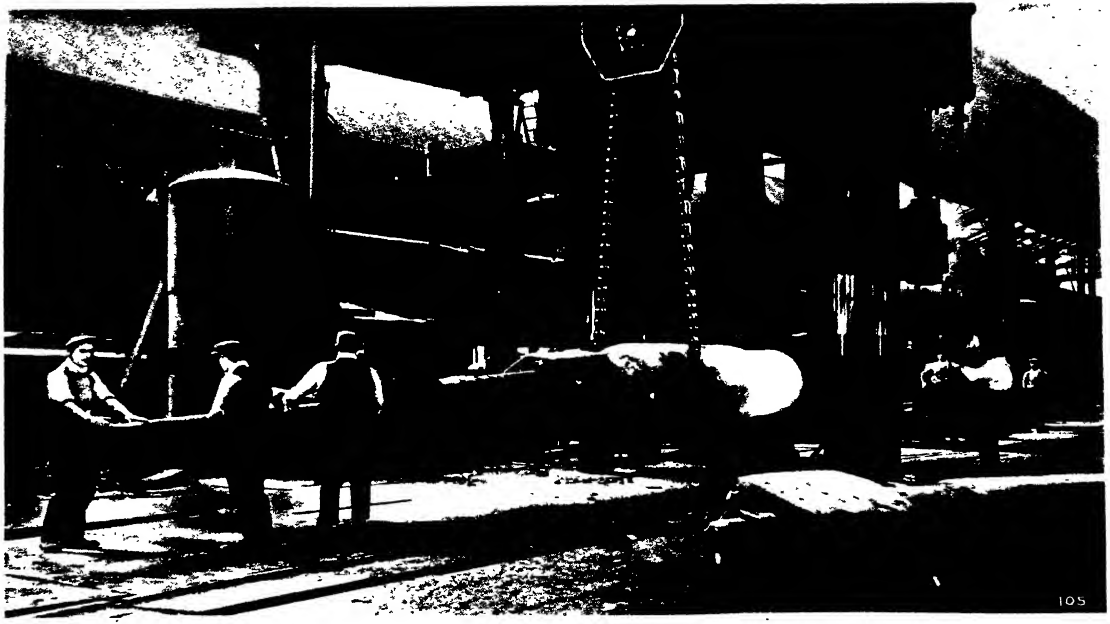
> " If a vessel full of water, closed on all sides, has two openings, the one a hundred times larger than the other, and if each be supplied with a piston which fits it exactly, then one man pushing

the small piston will equilibrate 100 men pushing the piston which is 100 times as large, and will overcome 99."

Joseph Bramah (1748–1814) constructed the first presses based on this principle, while to the late Lord Armstrong we very largely owe the development of machinery for the hydraulic storage and transmission of power.

The first hydraulic crane, made to Armstrong's designs, was erected on Newcastle Quay in 1846, water from ordinary town's mains being used. Pressure in connection with other installations was found inadequate and variable, and use was therefore made of water stored in tanks on high towers. Then Armstrong invented the hydraulic accumulator, upon which successful hydraulic transmission from central stations largely depends. The principle of the hydraulic accumulator is very simple. Within the accumulator is a vertical cylinder and ram. A very heavy weight is attached to the ram. When water is pumped into the cylinder the pressure increases until the ram rises and with it the weight. The downward pull of the weight, acting on the ram, maintains a constant pressure at the outlet to the cylinder, from which water may be drawn for doing heavy intermittent work, such as operating cranes, lifts, swing bridges, lock gates, boiler making and shipyard tools, winches and capstans and ship-steering gear.

Hydraulic power is unsuitable for continuous work, and uneconomical with high velocities and reversible motion on account of shock due to inertia. Its value lies not so much in actual transmission as in the possibility of concentrating immense power, by aggregating storage, for lifting or otherwise moving heavy concentrated loads. This gives it a special field of usefulness in which it is—and is likely to remain for a long time to come—unrivalled by other systems of transmitting and applying power.



(*Courtesy of Messrs. United Steel Companies, Ltd.*)

2,200-ton hydraulic press at work on an alternator rotor forging

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CHAPTER VI

ELECTRICAL GENERATION AND TRANSMISSION

I

Dynamos and Alternators

In the previous chapter we noted that until about a hundred years ago power was not often transmitted more than a few feet from its source. Then mechanical systems were developed which extended the range of transmission to a few miles. Now we shall turn to some of the latest and most remarkable of transmission developments, which enable us at will to transform energy of motion into electrical energy, transmit it if desired over hundreds of miles in any required direction, and then retransform it into energy of motion just whenever and wherever it suits us to do so. The coming of steam was revolutionary enough, changing the whole face of industry and creating an altogether unprecedented type of civilisation. But without electricity, steam power was like a friendly giant tethered to a stake. Electricity cut the tether and set Giant Power free. And now in the brief span of 100 years—fifty years where practical applications are concerned—electrical engineering has proceeded so far that mankind already has one foot upon the threshold of a new era ; an era in which power for every human need—on the farm, in the factory, the mine, the home, and for transport by land and sea—will be electrically transmitted and applied.

Though practical developments are so recent, observations on electrical and magnetic phenomena have been made for at least 2,500 years. The knowledge of antiquity, however, was very limited. Thales, who lived in the 6th century B.C., is said to have been aware of the attractive property of amber and loadstone (Diogenes Lærtius, i., 24).[1] Susruta, a Hindu physician of about the same period, gave an account of the surgical use of the magnet (Sarton, *Introduction to the History of Science*, p. 77). Euripides, born in 480 B.C., is said by Plato (*Ion*, 523D) to have called loadstone by the name "magnet." Plato himself lived from about 427 to 347 B.C., and in the passage referred to comments on the power of loadstone not only to attract iron rings, but to impart this power to the rings themselves. Another reference, both to loadstone and amber, will be found in *Timæus*, 80C. Aristotle, 384–322 B.C., relates that Thales made mention of the stone which moves iron (*De Anima*, A2, 405A, 19). Theophrastus, (*c.* 372–286 B.C.), to whom Aristotle bequeathed his library, remarks in his *History of Stones* (L, LIII.) :

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[1] Reference has been made to the Loeb translations unless indicated otherwise.

> "Lapis Lyncurius . . . has also an attractive power, like that of amber, and is said to attract not only straws and small pieces of sticks, but even copper and iron, if they are beaten into thin pieces. . . . Amber . . . has, like the before mentioned, a power of attraction. But the greatest and most evident attractive quality is in that stone which attracts iron."

It may be noted that there was considerable confusion on these matters in ancient writings, owing to the use of the word "electron" for both amber and an admixture of silver with gold ; and the name "magnetis lithos" for a variety of substances.

References to the properties of amber and loadstone will be found in Pliny's *Natural History*, XXXIV., 42, XXXVI., 25, XXXVII., 11 (Bostock and Riley's translation in Bohn's Classical Library). Mention is also made of the power of the torpedo to administer shocks (IX., 67, XXXII., 2). Pliny wrote in the 1st century A.D. Another writer of that century, Seneca, speculated at considerable length on the nature of thunder and lightning and their effects, and also mentioned the brush discharge now commonly called St. Elmo's fire : "In violent storms at sea there sometimes appear, as it were, stars settling on the sails." And again : "When Gylippus was on the voyage to Syracuse, a star appeared, resting on the very tip of his lance. In the camp of the Romans at times pikes appeared to be on fire" (*Quæstiones Naturales*, Bk. I., Sec. 1, translated by John Clarke under the title of *Physical Science*).

As Pliny wrote in 77 A.D., about twelve years after Seneca's death, and as they express similar views, it is probable that the former was familiar with the latter's work.

For other references to magnetic or electric phenomena or both in classical literature, see Lucretius, 1st century B.C., *De Rerum Natura* (translated by Cyril Bailey as *On the Nature of Things*), Bk. VI., lines 906–917; Dioscorides, 1st century A.D., *De Materia Medica*, Lib. V., Cap. CXLVII. (CXLVIII.); and Pausanias, 2nd century A.D., *Descriptio Græciæ*, v. 12, 7. At a much later time we find Eustathius, Archbishop of Thessalonica in the 12th century A.D., recording the emission of crackling sparks when dressing and undressing. To the early history of the mariner's compass we have already referred in Book I., Chap. VIII., Sec. 1; and all we need add here is that magnetic dip seems to have been observed in the first place by Georg Hartmann (1489–1564), and subsequently rediscovered in 1576 by Robert Norman; while the existence of magnetic declination was discovered, or rediscovered, by Columbus, who also noted that it varies at different points of the earth's surface.

We cannot do more than mention a few of those who contributed to man's slowly-growing knowledge of magnetism and electricity as the centuries rolled by. After the Epistle on the Magnet of Petrus Peregrinus in 1269 we find little marked progress until William Gilbert wrote his epoch-making book, *De Magnete*, in 1600. Of course there were many attempts to make a "perpetual motion" with the aid of magnets; Peregrinus, Carden, and Bishop Wilkins being among those who chased this particular mirage. But from the time of Gilbert onward a more scientific temper manifested itself, until we come to such outstanding names as Galvani (1737–1798), Arago (1786–1853), Volta (1745–1827), Ampere (1775–1836), and others who bring us down to the time of Michael Faraday.

It has been remarked by Professor G. W. O. Howe that:

> "If any one event can be regarded as the birth of electrical engineering, it is surely the discovery by Faraday in 1821 of the principle of the electro-motor; that is, that a conductor carrying a current in a magnetic field experiences a force tending to move

it. It is noteworthy that ten years elapsed before Faraday discovered, in 1831, magneto-electric induction ; that is, the principle of the dynamo. Four years later, Sturgeon added the commutator, or 'uniodirective discharger,' as he called it, and in 1845 Cooke and Wheatstone used electro-magnets, which Sturgeon had discovered in 1825, instead of permanent magnets." [1]

But whether we date the birth of electrical engineering from 1821 or 1831, the credit for making possible the vast developments which have since taken place in this field must be given to Faraday more than to any other one investigator.[2]

The electrical distribution of power begins with the generation of electricity by means of dynamos and alternators. The basic principle upon which modern electric generators operate is precisely the same as that underlying the elementary machine, consisting of a copper disc rotated between the poles of a permanent magnet, constructed by Faraday in 1831. In this a current was generated in the disc, flowing from shaft to rim, or *vice versa*, according to the direction of rotation, and was conducted away by two wires making sliding contacts with rim and shaft. Electro-magnetic induction is still the means by which we convert energy of motion into electricity ; though, as might be expected, modern dynamos and alternators are vastly more complex in construction, and more efficient in operation, than anything envisaged for long after Faraday's time. Even in 1879 the writer of the article on "Electricity" in the *Encyclopædia Britannica* (9th ed.) could remark : "It has been proposed of late to supply electromagnetic machines in lighting streets and workshops, and the experiment has been tried with some success."

All engineers, and many others, are aware that electric generators would by themselves be quite useless. To generate electricity they must be continuously provided with energy from some other source ; such as steam engines, steam turbines,

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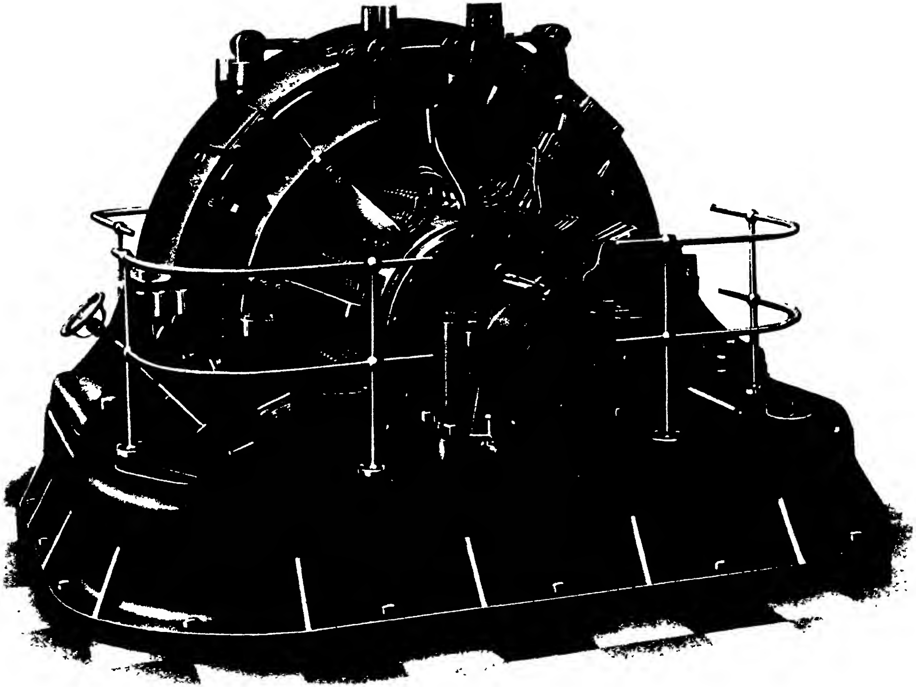
[1] "A Hundred Years of Electrical Engineering," an address to the British Association, 1924, by Professor G. W. O. Howe, D.Sc.

[2] In a letter in *The Times*, August 20th, 1930, Mr. Thomas Martin, General Secretary of the Royal Institution, points out that : "Faraday's discovery of electro-magnetic induction derives not from a single experiment, but from a series of experiments which he began on August 29th and carried on for many weeks into the early part of 1832."



(Courtesy of Messrs. W. H. Allen, Sons & Co., Ltd.)

A modern dynamo.

[To face p. 217.

vater turbines, or internal combustion engines. There is herefore no prospect whatever of electrical machinery eplacing steam and other prime movers altogether. It has lready replaced many such prime movers, and will replace nany more, but only because it is cheaper and more convenient to get power from a few large engines or turbines than from many small ones, once difficulties in the way of transmission to a distance have been overcome.

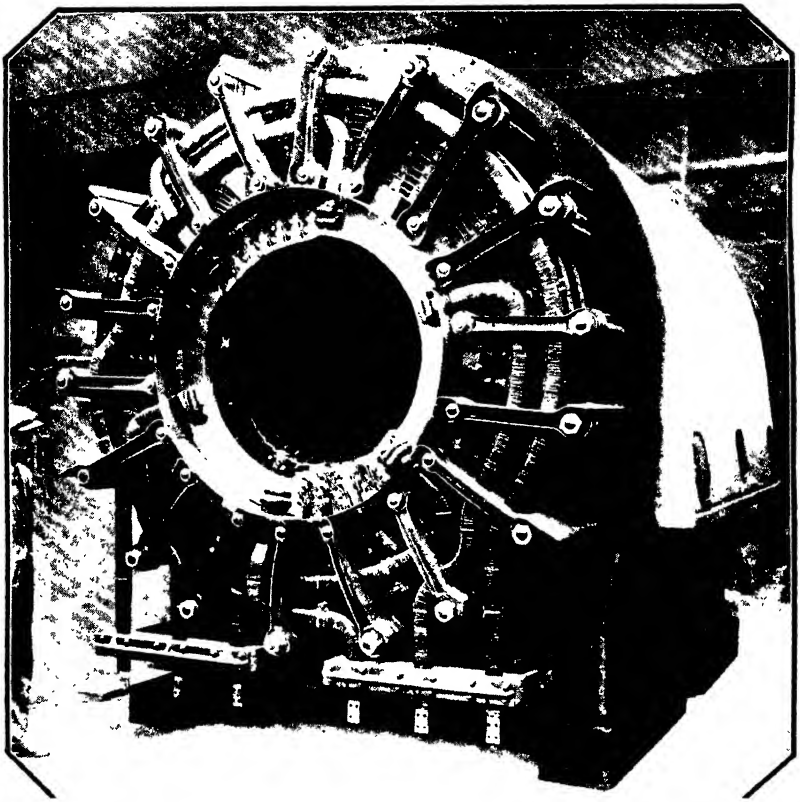
Electrical generating machinery is of two kinds ; the dynamo which delivers direct current, and the alternator which delivers alternating current electricity. Each consists essentially of an armature wound with copper conductors *in* which an alternating current is induced, and field magnets *by* which this current is induced. But in a dynamo it is invariably the armature which rotates, and the ends of the copper conductors thereon are electrically connected to a kind of cylindrical switch called a commutator. This reverses the connections with the external circuit just at the moment the current in the armature is reversing in direction. The result is, of course, that only direct current is led away from the machine. Alternators have no commutator, and are usually made with rotating field magnets (the rotor) and a stationary armature (the stator). Current for exciting the field magnets is obtained from a small dynamo called an exciter, mounted on an extension of the rotor shaft.

In the early days of electrical engineering most electric generators were dynamos. So long as electrical machinery was constructed only in small units—at first it was practically a case of one lamp, one dynamo—and no attempt was made to distribute electricity to any distance, direct current was satisfactory enough. It had many advantages. But it also had many limitations. S. Z. de Ferranti, one of the most creatively imaginative engineers the electrical industry has so far produced, was the first boldly to use alternating current at high voltages. Ferranti patented his first alternator in 1882 when only eighteen years old. Lord Kelvin (then Sir W. Thomson) joined forces with this precocious youth and the result was a Thomson-Ferranti alternator which beat all records for efficiency. A few years later Ferranti was making alternators for generating and distributing electricity at 10,000 volts; in which he was before his time, however, as he was in so many other matters.

Dynamos are still manufactured in large quantities. Nevertheless their use is almost entirely confined to the supply of current over small areas, as in a factory where no outside source of supply is available; or on board ship; or again where direct current is essential, as for electro-chemical purposes. Electric power stations which deliver electricity over a considerable area are now always equipped with alternators. The reason for this is that alternating high-voltage (or, as it is often called, "high-tension") current for long-distance transmission is much more economical and adaptable, as will be shown presently. Dynamos in general are unsuitable for delivering electricity at high voltages, owing primarily to the difficulty of collecting such currents through the rubbing contacts of commutators. In ordinary practice the limit for direct current is at present about 1,500 volts, though experimental work is being carried out which may make higher direct current voltages practicable.

Now there are several reasons why high-voltage current is used for long-distance transmission. With higher voltages less current may be passed through a power line without any reduction in the total power transmitted. Since losses in transmission vary as the square of the current, it will be seen that this is a consideration of first importance. Moreover the higher the voltage the smaller the wire necessary to carry a given current. This means less expenditure on cables, and less also on towers or other supports which must be constructed and spaced according to the weight they have to carry.

But, the reader may ask, why alternators? Well, to begin with, alternators can be designed to generate current at higher voltages than dynamos. Machines are now often wound for generating at 11,000 volts; at least one large 33,000-volt alternator has been running satisfactorily for some time; and the possibility of generating current at 66,000 volts has been



(*Courtesy of Messrs. C. A. Parsons & Co., Ltd.*)

Stator of a modern alternator.

[*To face p.* 21

scussed.[1] The primary reason for adopting alternators for gh-voltage transmission, however, is the facility with which is possible to transform alternating current from a low voltage a high one and *vice versa.* Thus current may be generated t any suitable pressure, transformed up for transmission, and en "stepped down" again to voltages which are regarded s safe and otherwise suitable for industrial and domestic use. t may also be noted that alternators can be constructed so that he current may be led away without exposed sliding contacts, and also—a very important point—motors for alternating current can be built on more robust lines than for direct current, primarily because here again commutators can be avoided.

Alternators are more complex, but are also more interesting to study than dynamos. A dynamo delivers current of a particular strength, measured in amperes, at a particular pressure, measured in volts. When connected up electrically to motors and lamps, and other apparatus which offers resistance, a complete circuit is formed round which the current flows against the total resistance. Ohm's law shows how pressure, current, and resistance are related. It will also be recollected that it is only necessary to multiply pressure in volts by current in amperes to get the power available in watts, or, if divided by 1,000, in kilowatts. These simple rules can, however, no longer be applied when dealing with alternating currents.

Alternating currents wax and wane, rising and falling in intensity as well as changing in direction. This can be illustrated by a simple diagram. Having first drawn a zero line of no pressure and no current, we can represent the rise and fall of current in one direction by a curve above zero, and the rise and fall of current in the opposite direction by a continuation of the curve below zero. We then get a wave-like line which rises to a crest, returns to zero, falls to a trough and again returns to zero ; thereafter repeating the process indefinitely. Electrical engineers call one complete crest and trough a cycle or period; the height of crest or depth of trough (representing maximum current strength) is the amplitude, and the number of cycles or periods per second the frequency. There is now a general tendency in Great Britain to adopt a

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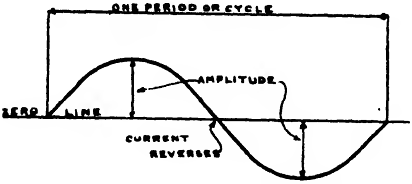
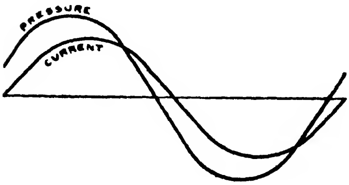
[1] See paper by Sir Charles Parsons and Mr. J. Rosen on "Direct Generation of Alternating Current at High Voltages," read before the Institution of Electrical Engineers on March 21st, 1929.



SINGLE PHASE CURRENT



CURRENT LAGGING BEHIND PRESSURE

Curves to illustrate alternating current and pressure.

frequency of 50 cycles a second. Very low frequencies are not suitable for electric lighting as the lights flicker with the fluctuations in current strength.

Again, an alternator can be designed to produce a number of individual currents. Each of these will go through a similar sequence of changes, but they will not pass through the same phase of strength at the same moment. This can be represented by a diagram similar to the last. Here we have three currents of equal frequency and amplitude, but differing in phase by a third of a period. This is called three-phase current, and is selected here because it is the type of alternating current most widely used. The three currents are generally combined in one transmission system, as will be indicated in a later section.

We still have one or two more differences between direct current and alternating current to record. An alternating current sets up a reaction against itself, known as inductance, preventing it from rising to a maximum as quickly as it otherwise would do, and also delaying its fall to zero again. We can illustrate this by showing a current curve lagging in phase behind the pressure curve.

Yet another peculiarity of an alternating current circuit is that it acts as an electric condenser. It is then said to have capacity. This has the opposite effect to inductance, helping the current to rise to a maximum value more quickly. It is very rare, however, for one effect exactly to balance the other.

The net result of these reactions, together with ordinary resistance, is called impedânce ; and this must be substituted for resistance when considering the behaviour of alternating currents. And the power delivered is no longer to be calculated by just multiplying volts and amperes together. No doubt in this way we get a figure which *apparently* represents watts, but owing to the difference in phase between pressure and current, the true watts (or power actually delivered by the alternator) will be less than the apparent watts. The ratio of true watts to apparent watts is called the power factor.

The power factor is of such vital importance in alternating current systems that we make no apology for inflicting these technicalities on the reader. It will be seen that as the power factor approaches unity—that is, as the difference between true and apparent watts decreases—so the economy of the system increases. On the other hand, the lower the power factor, the more power will be frittered away uselessly as heat. As the power factor is usually outside the control of alternator makers they ordinarily rate their machines as capable of producing so many kilovolt amperes (k.v.a.) ; or, alternatively, so many kilowatts (k.w.) at a specified power factor.

We have discussed alternating current generators at some length because we owe it very largely to these wonderful products of modern science and engineering that the elimination of drudgery is now no longer a dream of the remote future but a very real possibility of the present. In the next few sections we shall glance at some of the ways in which electricity is generated in the huge modern power stations of to-day, distributed over wide areas, and applied to the ever-increasing and ever more diversified needs of mankind for power.

2

Steam-Electric Generating Stations

Modern steam-electric generating stations are so full of interest that it is difficult to decide what particular aspects of their layout to select for discussion in the limited space at our disposal. The difficulty is increased by the fact that no two power stations are alike. Though there are general resemblances there are also striking differences, and it is impossible to say that one or another arrangement would be the more suitable under all circumstances.

Location is one of the first points to be considered in connection with central power station projects. Much has been said in recent years about the desirability of building steam-electric power stations close to the collieries from which fuel is obtained. No doubt under special circumstances a case can sometimes be made for doing this, but in general the proposal has under present circumstances little to commend it. The principal objection is that modern power stations require immense quantities of water, and these requirements can seldom be met by the water available at the collieries. For every ton of coal burned in large modern steam-electric power stations, from 400 to 600 tons of water are required for the condensers. This means that nothing less than a river can meet the needs of a super-power station if the plant is to be operated at highest possible efficiency.

(Courtesy of the A. E. G., Berlin.)

Klingenberg super-power station.

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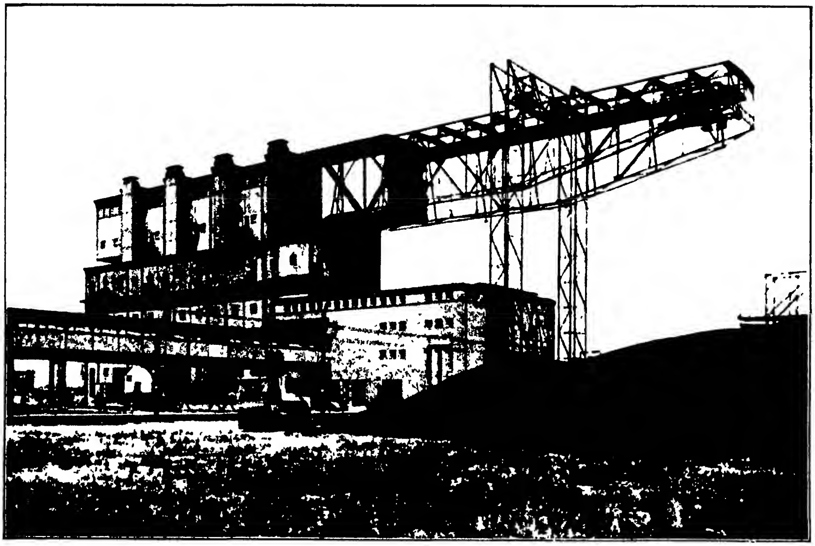

(*Courtesy of the A. E. G., Berlin.*)

Coal-handling and storage, Klingenberg super-power station.

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It is true that there is an alternative. As stated in an earlier chapter, the same condensing water can be cooled and used over and over again. But there is at present no cooling system which can compete with an unlimited supply of really cold river water, the lower temperature of which makes appreciably higher operating efficiency possible. Moreover, there are other considerations to be borne in mind. Many great cities and industrial areas are near to rivers from which large supplies of condensing water can be obtained. Building the power station at the river-side has therefore very often the double advantage of ready access to water, and proximity to an area requiring power. Add, finally, the possibility of bringing coal to the power station both by water and by rail, and there will be no difficulty in understanding why in practice the idea of locating power stations at the pit's mouth has so seldom been adopted.

In this connection it is also worth noting that the cost of coal transport relative to current generated has been reduced to a remarkable extent in recent years, due primarily to rapid progress in the design of steam-power plant. In the early days of electricity supply from 15 to 20 lbs. of coal were required per kilowatt per hour. Nowadays the most efficient power stations do not consume more than from 1 to 2 lbs. of coal per kilowatt hour, according to quality of coal used. We get some idea of what this saving means in terms of both coal conservation and reduction of transport costs, when we reflect that the total capacity of steam-electric power plant installed in twenty-four leading countries of the world is now over 40,000,000 kilowatts.

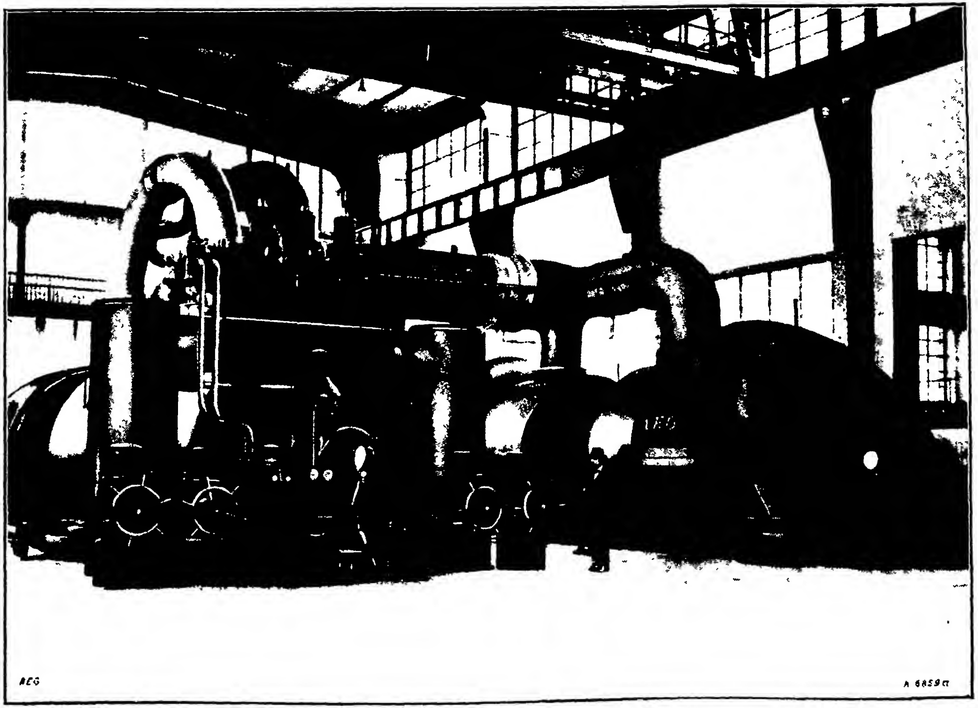
A fine example of an up-to-date and well situated plant is the great Klingenberg super-power station on the outskirts of Berlin. We cannot do better than select this station to illustrate a typical sequence of processes involved in the generation of electric power by steam on a large scale, including the use of powdered fuel.

The Klingenberg power station is arranged so that coal is taken in at one end and electric current delivered at the other. The procedure is as follows: Coal is first delivered into storage yards with a capacity of 135,000 tons. From here it is elevated as required and delivered into bunkers above the pulverising plant, powdered coal only being used at the boilers. From these bunkers the coal, after being dried, passes to the pulverisers, which reduce it to a fine powder. Thereafter it is pumped through pipes to another set of bunkers above the boilers.

Underneath these bunkers there is a distributing arrangement which controls the supply of powdered coal to each of sixteen boilers. Here the fuel, carried to the combustion nozzles by a blast of pre-heated air, burns in great sheets of flame, like so much gas, as it issues from the nozzles into the combustion chambers. Steam is produced at 500 lbs. per square inch and superheated to a total temperature of 770° F. Each boiler has a maximum continuous output of about 80 tons of steam an hour, and so efficient and automatic is this portion of the plant that only one man is required to attend to four boilers. An operating platform is provided for each attendant, complete with control gear, writing desk and telephone.

From the boiler-house steam passes through the main pipe lines to the power plant, consisting at present of three four-cylinder turbo-alternator sets of 80,000 kilowatts full load capacity each, and three smaller sets of 10,000 kilowatts capacity each which run on steam afterwards used for heating the boiler feed water. This is equivalent to a total of about 360,000 horse-power. The sets are, of course, capable of taking an overload for limited periods, and in the winter months the total demand for power may rise to 300,000 kilowatts. Ultimately the capacity of the plant will be increased to 540,000 kilowatts.

In accordance with general (though not universal) practice, the condensers are directly below the main turbines. The condenser pumps, which are normally driven by electric motors but can also be operated by small steam turbines in case of emergency, are located in an adjoining section of the building. This leaves the turbine operating floor clear, with ready access to the turbines and alternators from all sides. Three-phase current is generated at 6,000 volts, or, as it is



(*Courtesy of the A. E. G., Berlin.*)

80,000 KW. steam turbine, Klingenberg super-power station.

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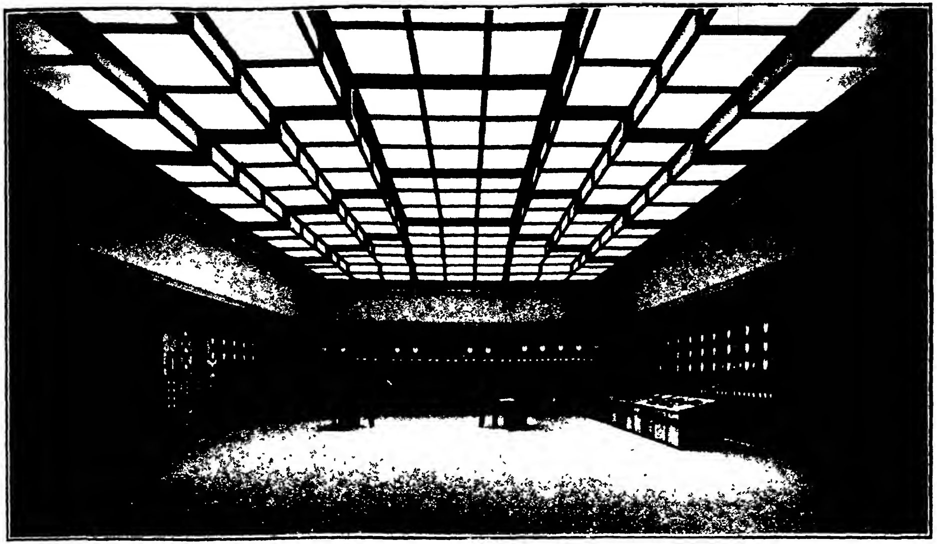

{Courtesy of the A. E. G., Berlin.

Control room, Klingenberg super-power station.

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now often written, 6 kilovolts. This is stepped up by transformers in the power station to 30,000 volts (30 k.v.) and then led by underground cables to the main switchhouse. From this building the current is delivered into the network of transmission mains which covers the area of supply and links up with other power stations.

One of the most interesting features of the Klingenberg power station is the central control room. The dimensions of the plant as a whole are such as to make direct " unit " control of all sections impossible. The turbo-generator section alone, though containing only six sets, is 462 feet long. The only possible method of ensuring adequate, co-ordinated control under such circumstances is to arrange for automatic equipment, with remote control and remote operation of all indicating and feeding mechanism. This can now be accomplished by electrical means. The central control room has been equipped on this basis with indicating and recording devices for supervising the operation of the whole station. In this way the engineer-in-charge can take as full responsibility as though he actually had the whole of the plant at his finger ends. He controls his 360,000 mechanical horses more effectively than most of us could control a coach and four.

Though there are few power stations so large as Klingenberg there are many just as interesting in other parts of the world. And it may be recorded here that the biggest power stations are not invariably the most efficient. There are, in fact, smaller plants both in Great Britain and America which could compete on level terms with the best that has so far been accomplished by super-power development.

3

The Diesel Engine and Electric Generation

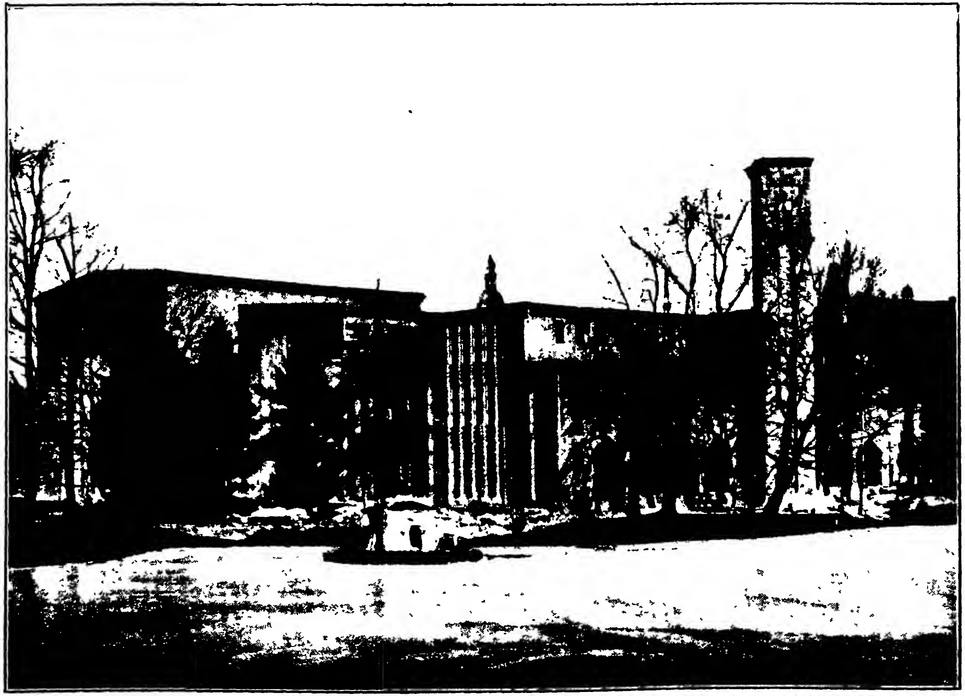
The large-scale Diesel-electric power station is a prospect of the future rather than an actuality of the present, so that it will not be necessary to make more than passing reference to the use of this type of plant for the generation of electricity.

The Diesel engine has many advantages, such as its high efficiency, and the ease with which it can be started up and be fully loaded within a few minutes. But it also suffers under the disability of high initial cost ; moreover, it can only be made in relatively small units—though of course, great strides have been made in this regard in recent years. Even so, the largest size of Diesel engine visualised at the time of writing is one of 20,000 brake horse-power ; that is, less than one-tenth the capacity of the largest steam turbine now in operation.

So long as the Diesel engine was confined to the single acting, four-stroke cycle, high initial cost made the manufacture of even moderately large units out of the question. Adoption of the double-acting principle and of the two-stroke cycle led to greatly simplified designs and a considerable reduction in weight and overall dimensions for a given output. This, of course, also meant less expenditure on foundations, so that in one way and another remarkable progress has been made towards a solution of the problem of high initial cost.

Again, there has been great progress with those details of design which affect running costs, and reliability ; whilst early difficulties in regard to cyclic irregularity of speed—fatal where the running of electric generators in parallel is concerned—have now been effectively overcome. And there is every prospect that further developments will before long bring the Diesel engine into an even more favourable position for power station service, particularly in regions where the price ratio of fuels favours the use of oil.

The utilisation of waste heat, the development of an engine operating on powdered coal instead of oil, the production and utilisation of cheaper fuel oils, are a few of the possibilities which almost at any time now may make the Diesel engine a more favourable proposition for large-scale electric power generation. But it is not yet a serious competitor with the steam turbine where continuous service and large units are required. Its usefulness at present, and possibly for some little time to come, is likely to be confined within the limits of the small power station, of larger stations in regions where the price of oil in relation to that of coal is sufficiently favourable, and



(*Courtesy of the A. E. G.*)

Diesel-electric power station, Cottbus.

of peak load and stand-by service in hydro-electric and other stations subject to considerable fluctuations of load.

The development of the Diesel engine (as also that of the steam turbine) for marine service is a matter which falls outside the limits we have set ourselves in this work.

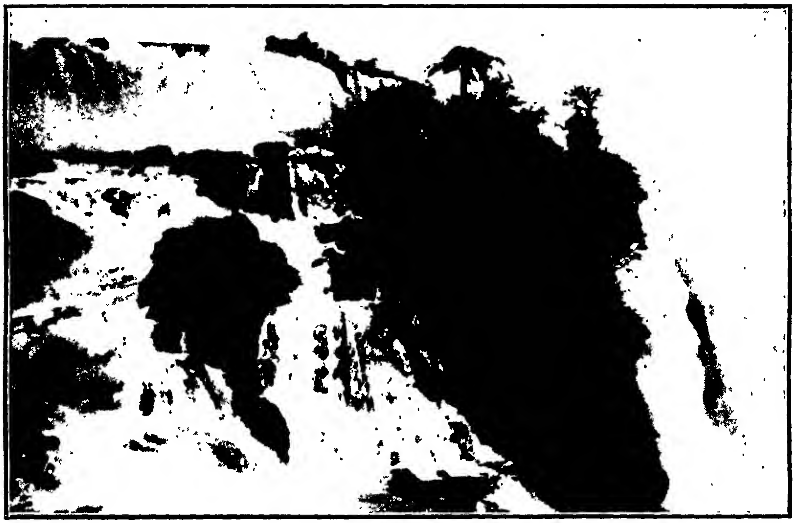
4

Hydro-Electric Generating Stations

The ideal water-power site is one where a high head of water, adjacent to an ample demand for power, can be utilised. It is now possible to transmit power economically over several hundred miles, but long distance transmission naturally sends up the cost of power ; and waterfalls will not normally be used unless electricity can be supplied at a price not exceeding that of steam-electric power generated on the spot. That is why falls such as those on the Brazilian-Argentine and Brazilian-Paraguay borders, each higher than Niagara, and wider than Niagara and Victoria Falls put together, remain unharnessed. They are at present too remote from centres of demand for power.

Much has been said in recent years about the possibilities of water-power, but the economic and practical considerations which at present limit hydro-electric development are not always sufficiently appreciated. In the first place the capital expenditure involved is usually much heavier than that for a steam power station of equivalent output. There are many items to be considered quite apart from the power station and the actual plant. A dam must be constructed, and under some circumstances this may be a very costly item indeed. Absence of suitable rock foundations for a dam may even be sufficient to prevent utilisation of a fall of water altogether. Then arrangements must be made to impound and store water on an area of many acres, sometimes many square miles. The slope of the river and available head, the discharge of water, fluctuations in discharge between seasons of rain and drought, liability to sudden flood, or to accumulation of ice, the possibility of providing additional water storage sites upstream, are all considerations affecting cost. The National Electric Light Association of America estimates that it costs from two to five times as much to build, say, a 10,000 horse-power hydro-electric plant, including transmission, as it costs to build a modern 10,000 horse-power steam plant. That is, the interest and taxes on the hydro-electric plant will be from two to five times as much as the interest and taxes on a steam plant of similar capacity. The extra charges due to interest on capital expenditure and taxation may even in some cases exceed the whole cost of coal required for the steam plant.

Without going into detailed consideration of the many factors on which hydro-electric development depends, we may sum up by saying that there is not much prospect of materially reducing the capital expenditure involved ; and since the efficiency of a modern hydro-electric power station is already over 90 per cent., while operating charges are relatively low, it would be unwise to anticipate any very sensational improvement upon present practice. Increased use of water power will depend rather upon reducing the cost of transmission so as to bring additional falls of water within economic range, and also upon creating new industrial areas near to potential water powers. Modern steam-electric power stations, on the other hand, only utilise about 25 per cent. of the heat units in the coal burned, while the operating charges are relatively high. Thus it appears that there is much greater prospect of reducing steam-electric than of reducing hydro-electric costs of power production. This means that where both methods of producing power are available, the hydro-electric power station may very well find it increasingly difficult to compete. So far as the layout of the power station itself is concerned much depends on the head and volume of water available, which will determine what type of turbine is to be installed. These considerations affect the substructure, the water passages in which react in their turn on the spacing of the units. These are commonly arranged in a line parallel to the length of the power station. Except for low head turbines, water is brought to the power house through a pipe or pipes, called the penstock, which may terminate at the upper end in an enlargement of a



(Courtesy of Mr. R. G. Shearer, Buenos Aires.)

The Falls of Iguazu, South America.

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canal from the reservoir called the forebay. Water from a reaction turbine discharges through a passage known as the draft tube. This is a cone-shaped passage or pipe which, owing to its increasing diameter, reduces the exit velocity of the water and so increases the efficiency of the turbine.

Margins of safety must be allowed both in layout and construction to a degree not necessary with any other type of power plant. This is because the natural forces which are to be curbed, controlled, and utilised are much more variable and uncertain than the power of steam or even of explosive mixtures. One very important safety device is the surge tank. This acts as a safety valve, relieving the penstock from dangerous rises in pressure.

Water power was first used for generating electricity at Appleton, Wisconsin, in 1882. The output of the plant was about the equivalent of 1 horse-power. The largest units in the world to-day are installed in the power station of the Niagara Falls Power Company.[1] Each turbine develops 70,000 horse-power, while the total capacity of the Chippawa plant of the Ontario Hydro-Electric Commission, also at Niagara, is over 500,000 horse-power. Yet even these developments will probably be dwarfed some day by the utilisation of the vast water powers of South America. In addition to two great waterfalls we have already mentioned, there are others in that continent of almost inconceivable majesty and might waiting to be harnessed in the service of man. The famous Kaieteur Falls in British Guiana have a single vertical drop of 740 feet, and a total fall nearly five times that of Niagara. And of the 54,000,000 potential horse-power available in South America, less than 1,000,000 has so far been developed.

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[1] The Dnieper power plant of the Soviet Union, begun in 1927 and now in 1931 about 50 per cent. completed, will be when finished one of the largest hydro-electric plants in the world, with a total capacity of 558,000 kilowatts. It is interesting to note that in association with some of their new power stations the U.S.S.R. are creating groups of industries to absorb the power generated. Thus, the Dnieper industrial combine will include a steel plant, an aluminium plant, and a chemical plant, besides the necessary housing for the workers. (See *Power Engineering and Finance*, February, 1931.)

All water power figures should be accepted with caution. " Developed power is usually given in terms of the capacity of the installed water-turbines, which may be several times the potential power available 90 per cent. of the time."—*U.S. Geological Survey Report.*

5

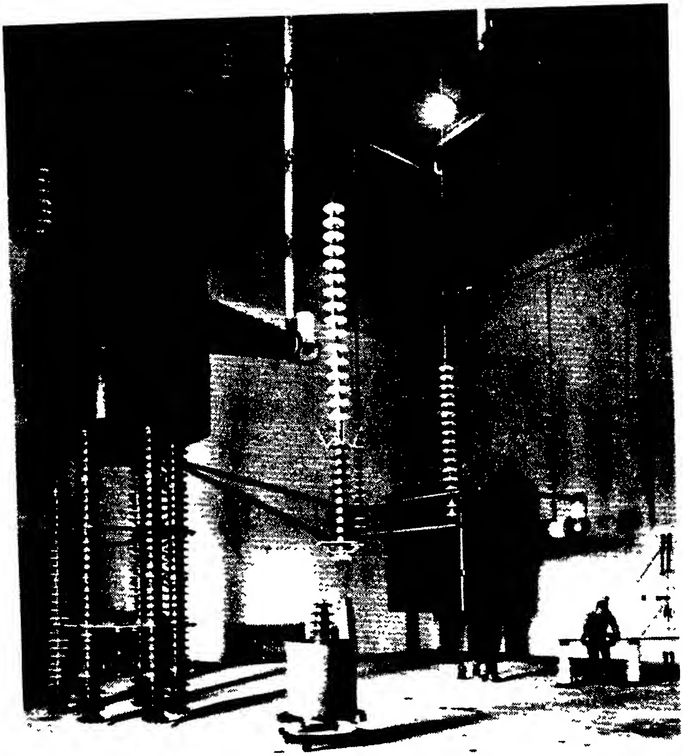
Electrical Transmission and its Significance

In a simple long-distance transmission system the supply voltage is first stepped up by means of transformers to a very high pressure. When it is required to " tap " the high pressure mains, connections are taken to a sub-station consisting of step-down transformers, where the voltage is reduced to a moderate pressure for local distribution. Connected to the local distribution mains there are more step-down transformers, which give a further reduction to a pressure suitable for lighting and power circuits.

The principle governing the construction of transformers is very simple. If two independent coils of wire are wound on an iron core, and an alternating current is passed through one of them, then another alternating current will be induced in the secondary coil. When the windings are identical in length and diameter of wire, the voltage in each will be the same. But if there is a difference in the number of turns of wire in the two windings, then the difference in voltage will depend upon the ratio between the number of turns in each. Thus, a transformer with 100 turns and 1,000 turns in its primary and secondary windings respectively would step-up the voltage in the ratio of 1 to 10. Current supplied to this transformer at 6,000 volts, for example, would theoretically induce current in the secondary winding at 60,000 volts. At the same time the current would be proportionally stepped-down to one-tenth the value of that flowing in the primary circuit.

In practice an allowance must be made for losses in transformation which will rarely exceed 2 per cent. in the average commercial transformer. The losses make themselves manifest in the form of heat, so that cooling arrangements—especially where large-scale high pressure transformation is concerned—are a prominent feature in modern transformer design.

To appreciate the importance of the part played by transformers in long-distance transmission, we have to remind ourselves that the loss of energy for a given size and length of wire is proportional to the *square* of the current. Thus with a



(*Courtesy of* "*World Power.*")

Testing transformers at a high-tension research laboratory.

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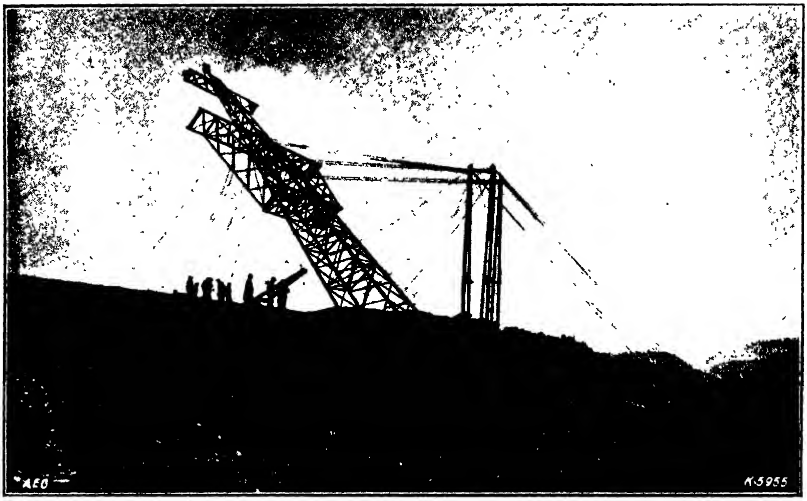
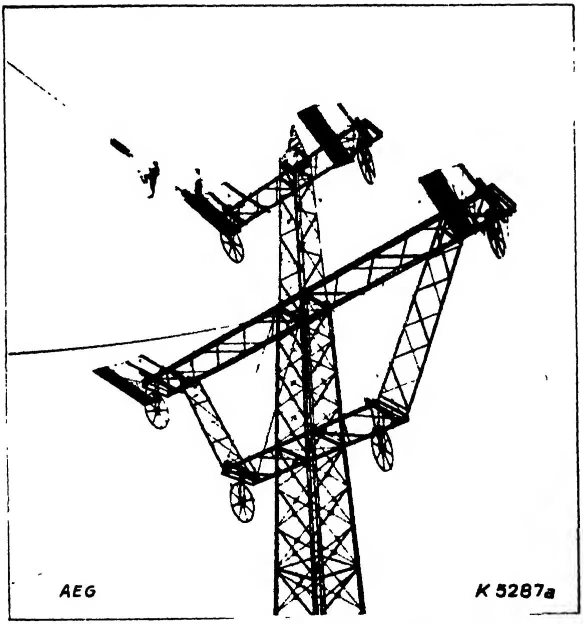


Hauling a 45-ton tower into position.



(*Courtesy of the A. E. G.*)

Men at work on transmission cables and tower.

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current of 1,000 amperes transmitted at 1,000 volts there will be a loss of energy 10,000 times greater than when a current of 10 amperes at 100,000 volts is passed over the same wire. Yet the energy supplied to the wire is the same in each case.

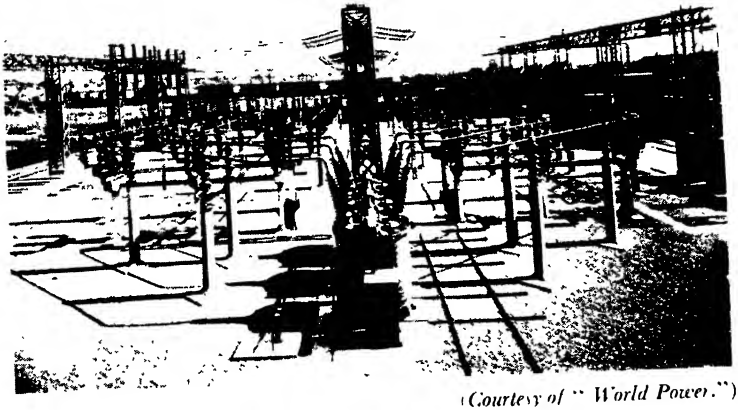
By suitably connecting the windings, three-phase current may be transmitted through four wires ; the three return wires being combined in one common return. When the three currents are equal in magnitude and out of phase with each other by equal amounts, even the one return wire may be dispensed with, since under these circumstances the sum of the three currents flowing in it at any moment will be zero. This makes it possible to transmit three-phase current through three wires—quite a different matter, of course, from the ordinary three-wire system used for direct current.

High-tension lines are usually carried on pylons or towers, which are now rapidly becoming a feature of the landscape between industrial towns and areas. Another noticeable development is the practice in recent years of erecting heavy switchgear and associated apparatus out of doors. Owing to the large scale on which power stations are now being built and equipped, as well as to the decrease in the reactance of modern alternators and transformers, apparatus of unprecedented proportions is now required to protect the plant from the tremendous stresses which may be set up by short circuit currents. This apparatus takes the form of huge current-limiting inductance coils, called reactors. These, too, may be seen in the open, outside the power station building containing the plant it is their duty to protect. On all such apparatus massive and elaborate insulators are much in evidence, with their numerous collars to minimise the tendency of the current to short-circuit by flashing across.

The pressure at which electricity is transmitted has increased at an average rate of about 6,000 volts a year during the past thirty years. The present maximum is 220,000 volts, though an international line which will eventually link the steam-power plants on the lignite fields of Cologne with hydro-electric plants in the Austrian Alps is being designed to transmit at 380,000 volts on completion. This line will cover a distance of about 300 miles. One of the longest transmission lines in the world so far constructed is that of the Southern Californian Edison Company, which transmits power 250 miles from Big Creek, on the South Fork of the San Joaquin River, to Los Angeles. This also operates at a pressure of 220,000 volts. And only thirty years ago it was considered quite an event to have transmitted electricity over thirteen miles at a pressure of 4,000 volts!

There appears to be no definite physical limit to the range of electrical transmission. Laboratory investigations have been carried out in America by F. W. Peek, Jr., at the stupendous pressure of 5,000,000 volts. There are other limitations, however, some of which may prove to be very difficult to overcome. One serious difficulty, for example, is a phenomenon known as corona, which occurs when two wires, with a great difference of pressure between them, are suspended near one another. Above a certain voltage, depending largely upon spacing and size of wires, a loss of power occurs, due to the rupturing of the insulating capacity of the surrounding air. A continuous passage of energy then takes place which may be an appreciable proportion of the total transmitted. Corona manifests itself as a bluish-coloured luminous cloud surrounding the wires, accompanied by a characteristic hissing sound. To increase the size of the conductors, or to carry them so far apart as to necessitate separate line towers, would normally cost more than is saved by the adoption of high-tension current. In other words, the losses due to corona effect may very well prove to be the controlling factor in high-tension transmission. Possibly a way will yet be found—through progress with the mercury rectifier, perhaps, or some other outcome of intensive scientific research—of readily and economically converting alternating to high-tension direct current. This would greatly simplify extra high-tension transmission by reducing corona effects and also eliminating inductance, though some way of reversing the process would still have to be devised.

The value of long-distance transmission is far from being confined to the fact that sources of power can now be utilised which previously were out of reach of existing " load " centres.



(Courtesy of "World Power.")

Outdoor switching station at Budapest.

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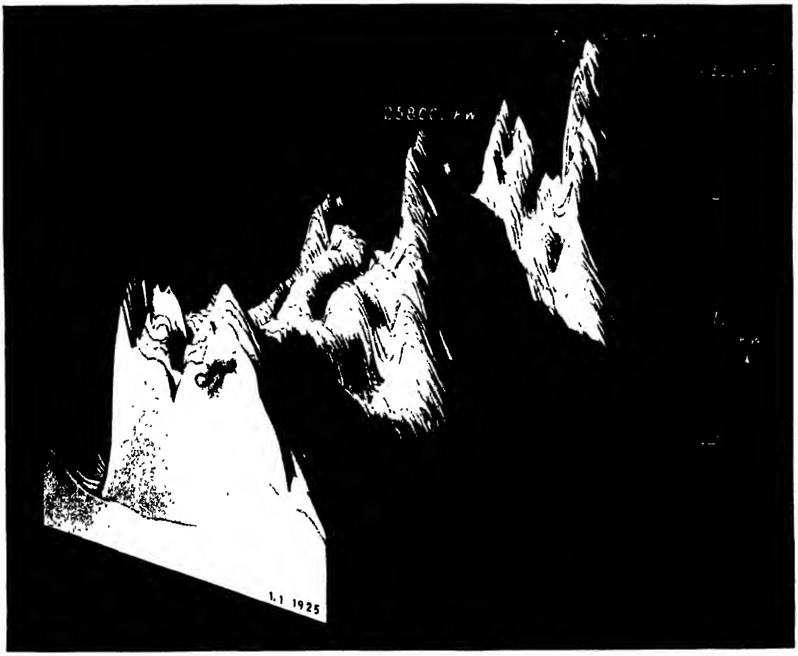
25800 kW
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(*Courtesy of the A. E. G.*)

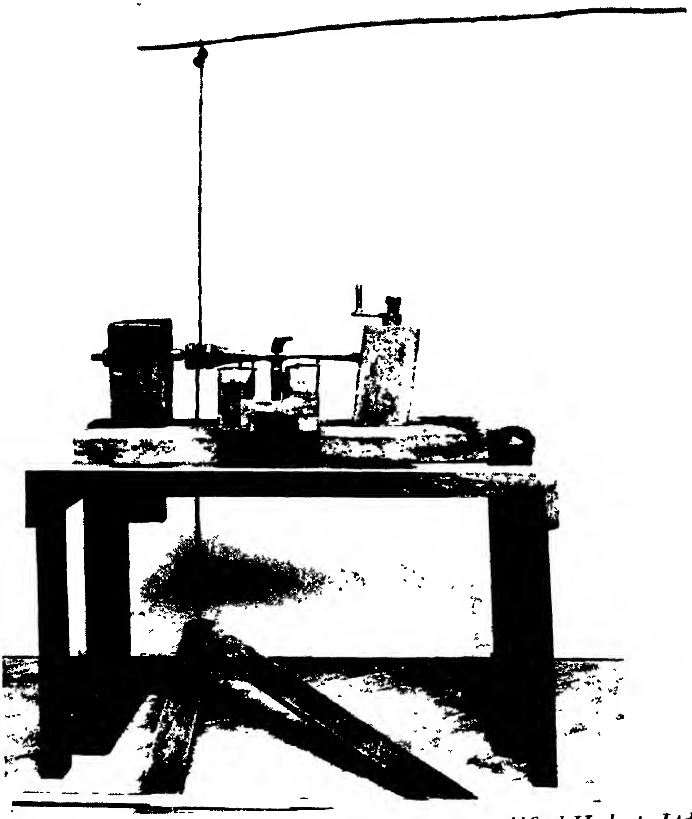
" Load mountain," Berlin Electricity Works.

[*To face p.* 233.

Another boon which it can confer on mankind is the possibility of redistributing populations over the great open spaces of the world ; relaxing ties which have hitherto restricted the movements of great numbers of people to small and heavily congested areas. Closely bound up with this is the prospect of a radical change in agricultural methods following upon extensive rural electrification. Even to-day in the United States—the country which has hitherto utilised external power more than any other—agriculture is for the most part dependent upon animal and man power. Yet this industry uses nearly 50,000,000 horse-power—more than all the factories put together. Many problems still remain to be solved before energy can be distributed economically over thinly populated areas, but while ten years or so ago rural electrification was looked upon as altogether impractical, it has now already become a recognised feature of large electric supply projects.

One of the greatest advantages of high-tension transmission is the possibility of effecting enormous economies by interlinking power stations, so that much bigger units can be installed for supplying energy into a common transmission network. The electrical industry is in the unique position of having no facilities for storage. If there is only a small demand for power most of the time, with an occasional " peak " load for short periods, then sufficient plant must be installed to meet the peak demand, even though much of the plant capacity is unused most of the time. This naturally adds greatly to the cost of electric service, the cost increasing in proportion to the excess of maximum or peak demand over average demand for power. The ratio of average demand to maximum demand is known as the load factor, and power station engineers are constantly seeking to improve this factor by eliminating excessive fluctuations. An excellent idea of the way demand on a power station for power may fluctuate both daily and throughout the year can be obtained from the accompanying illustration. Curves representing the variation each day are cut out in cardboard and then assembled together for the year. The result is a three dimensional representation similar in appearance to a peaky range of mountains. The ravines and valleys represent the minimum loads, and the peaks the maximum loads. Since different power stations may have very different load characteristics, it will be clear that interconnection will tend to eliminate fluctuations, and thus make it possible to operate the whole group with greater economy.

To sum up. The supreme significance of electrical transmission lies in the facility with which power on a scale hitherto undreamed of can be applied as, when, and where it may be required. For where men desire to go, there cables may go also. With this splendid gift of science has come the promise of a new way of life for all mankind, the possibility of human existence being freed for ever from the body and soul destroying drudgery of uncongenial toil.



(*Courtesy of Messrs. Alfred Herbert, Ltd.*)

The pole lathe.

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CHAPTER VII

THE DEVELOPMENT OF THE TOOL WITH THE COMING OF POWER

I

The Evolution of Power-operated Tools

It is as true of our modern world as of that in which Lucretius lived, that " all things waste away little by little and pass, foredone by age and the lapse of life." So it is that the ceaseless wasting away of machinery must be accompanied by a ceaseless process of repair and renewal, without which modern machine production would speedily come to a standstill. In consequence our productive equipment is always changing, and from this point of view represents a flowing rather than a fixed asset. The "flow" is maintained by power and tools, both of which are necessarily antecedent to machinery in general. It will therefore be appropriate, before leaving the subject of power plant and passing on to a consideration of the materials of power, to make some brief notes on the power-operated tools, on which modern machinery is itself so largely dependent for its existence.

So long as goods were produced by hand, with the aid of a few simple machines operated by hand or foot, there was no inducement to construct elaborate tools. The primitive bow-lathe of ancient Syria, its successor the pole-lathe, and the forge hammer worked by a water-wheel, were until 150 years ago practically the only forerunners of the wonderful power-operated tools of to-day. A device resembling the slide rest was known as early as the 16th century, but it was not until Henry Maudslay re-invented it in 1794 that it was developed into one of the most valuable adjuncts to accurate workmanship that has ever been devised. Joseph Bramah, Maudslay's employer at the time, also contributed materially to the development of power-operated tools for wood and metal working. Wood-working machinery was subsequently developed by Bentham and Brunel.

In 1775 John Wilkinson contributed to the manufacture of Watt's engines by inventing a cylinder-boring machine, which was a considerable advance upon anything previously used. From this time onward a number of machine tools were designed and made at the Soho foundry.

Maudslay's screw-cutting machines, the further development of the screw thread system by Joseph Whitworth, the inventions and improvements of Richard Roberts, Joseph Clement's planing machine, Nasmyth's steam hammer, were all notable steps in the evolution of power-operated tools. But no engineer, not even Maudslay, had a more profound influence upon the accuracy of such tools than Joseph Whitworth, who was the first to devise a method for securing a true plane surface, without which accuracy in the modern sense of the word would be impossible.

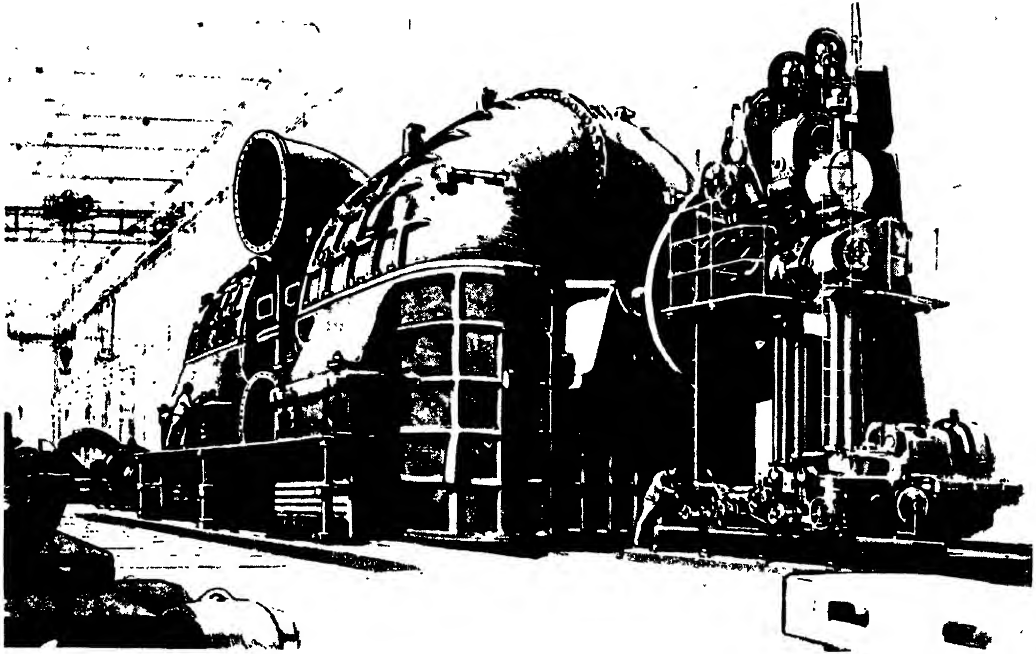
To the United States of America we owe the invention and development of power-operated tools suitable for mass production of interchangeable parts. In 1836 Colonel Colt invented the revolver, and by the middle of the century Eli Whitney and Colonel Worth had established large factories for manufacturing small arms on the interchangeable principle. The first capstan lathe appeared shortly after Colt's revolver had established its reputation. The firm of Pratt and Whitney developed the capstan lathe, adding the turret which revolves automatically at the end of the return stroke of the slide.

In 1873 Christopher M. Spencer made the first auto-screw lathe. Since that time America has practically been without a serious competitor in the production of typewriters, cash registers, sewing machines, cheap clocks and watches, and the highly ingenious tools required for their manufacture.

2

Some Modern Power-operated Tools

In so far as tools and power are paramount necessities of civilisation, it is of the highest significance that enormous



(*Courtesy of Messrs. Brown, Boveri & Co., Ltd.*)

Machining the low pressure cylinder of 160,000 k.w. steam turbine. A modern machine-tool at work.

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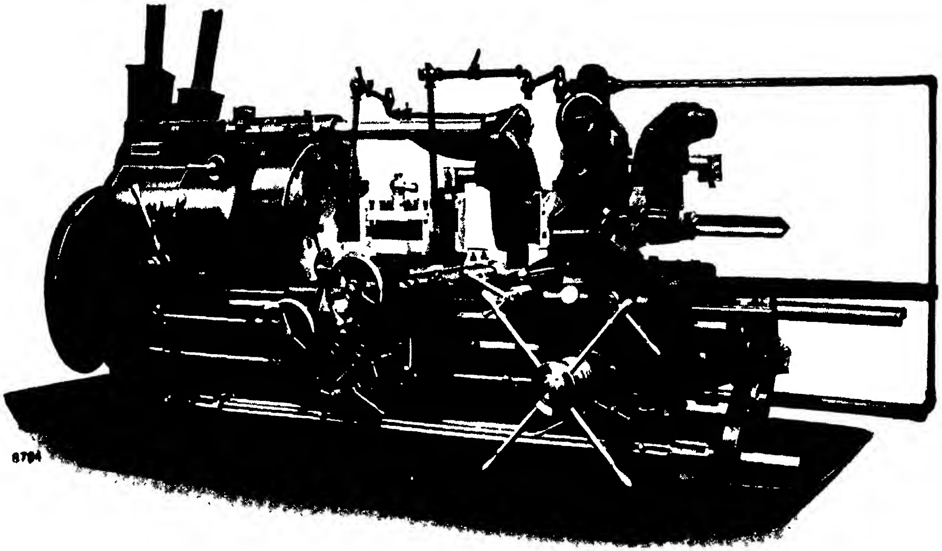
strides have been made in recent years in the design and manufacture of power-operated tools. So many new forms have appeared, so many new ideas have been incorporated with designs already existing, that instead of only a few leading types a modern engineering works may be equipped with an almost bewildering variety of tools. Some are specially adapted to the performance of one particular function only, some are capable of performing a number of functions, some again possess characteristics in common with others that differ from them altogether in general design and application. It has been aptly said that their name is not only legion, but diversity. Various attempts have been made to classify power-operated tools, but none of the classifications suggested has proved satisfactory. The fact is that all proposals so far made—the broad division, for example, into mechanisms in which the tool moves, and mechanisms in which the work moves—are hopelessly inadequate: attempts at simplification which fail to simplify and may easily mislead. Some day, perhaps, an engineer will do for tools in general what Linnæus did for botany; studying their "morphology" and functions, the arrangement and function of their various parts, noting resemblances and differences, and then classifying by species, genera, orders, classes, and tribes.

Here we shall note some of the more interesting features and trends in present-day design. We may note, for example, that there is an almost universal tendency to substitute rotary for reciprocating motion, except where work is performed by percussion. Owing to the way in which the human frame is constructed, all tools deriving from the past involved reciprocating motion in their early applications. But when external power is applied, reciprocating motion soon tends to disappear, as in the lathe, the circular saw, the band saw, numerous wood-working machines with rotary cutters, and various types of drilling, boring, milling, and grinding machines. Of power-operated tools in which reciprocating motion is still retained, the most widely used are slotting, shaping, and planing machines, and the various types of power hammers and rock-boring tools.

Tools are essentially labour-saving devices, and among the most notable of recent developments is the tendency to eliminate labour, even in minor details, so far as it is possible to do so. This has been effected most strikingly in the design of tools used for repetition work by extension of the automatic principle. At the same time there has been a great increase in the accuracy, speed, and scale of working. Special purpose lathes are now made with as many as a dozen tools operating at once, the tools moving up to the work and passing from operation to operation in quick succession without being touched. As the finished articles fall into a tray below, the raw material moves forward, while the tools come automatically into position for commencing all over again. This continues so long as the machine is supplied with power and fed with raw material. A man standing by watches over the operation of several of these " automatics," collecting and removing the finished articles from time to time, and stopping the tools if anything goes wrong. Another way in which labour has been greatly reduced is by the substitution of gear-boxes, not only on lathes, but on many other machine tools, for the old crude method of changing speed by moving a belt by hand from step to step on a pair of stepped pulleys. The best modern lathes are so designed that alterations in cutting speeds and feeds are effected by the simple process of moving levers over feed plates, the levers selecting, moving and engaging gears in totally enclosed gear-boxes. Even the tedious work of changing gears by hand for screw-cutting has also been greatly reduced on many modern lathes by the addition of quick-change screw-cutting gear-boxes.

The actual cutting tool is by no means always of steel. Diamonds and other materials are sometimes used. A suitably shaped diamond may be electro-plated and soldered into a holder, but modern practice is to set and braze the diamond into a steel holder. Heat also is, of course, one of the most useful of " tools " for cutting and moulding purposes. Indeed, the use of the oxy-acetylene flame for cutting metals provides a truly remarkable illustration of man's rapidly increasing dominion over the materials he works with.



(*Courtesy of Messrs. Alfred Herbert, Ltd.*)

A modern combination turret lathe.

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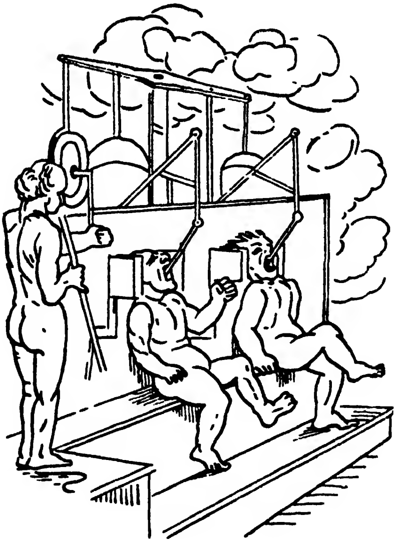
So far as metal tools are concerned, it may be noted that in the process of doing work a certain proportion of the energy applied is always lost in the form of heat. The heat generated has quite obviously an important influence upon the type of tool used, and selection of the material of which it is made. The ability of the tool to withstand reactions due to heating is in its turn of primary importance in its effect upon speed of working. Many new steels have been evolved, resulting in a complete revolution in the rate at which work can be performed. But this is a subject on which we can enlarge more conveniently when discussing the materials of power in our next book.



With best wishes

R. A. Hadfield

May 1930

Sir Robert A. Hadfield, Bart., D.Sc., F.R.S.

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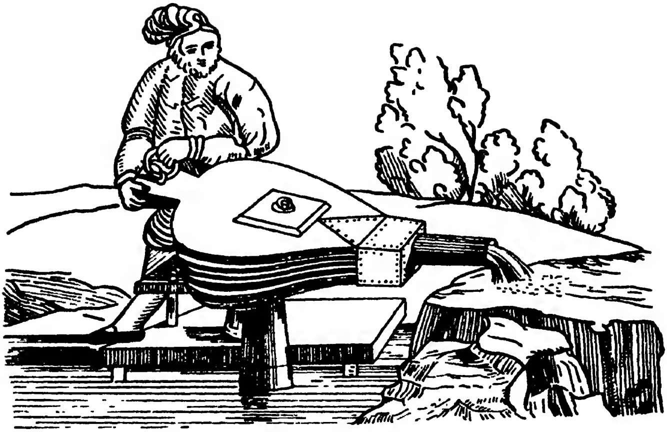
BOOK THREE

THE MATERIALS OF POWER

"We tore the iron from the mountain's hold,
By blasting fires we smithied it to steel."

JOHN MASEFIELD.



Water-raising, 16th century. Vegetius (Effurt A.D. 1511)

CHAPTER I

COAL

I

Early Days in the Coal Industry

It would be superfluous to stress the importance of coal in relation to man's quest for power. When mining for coal began we do not know, though we have seen that mining for other substances, such as flint, began before the dawn of history. It has been suggested that the Romans obtained their knowledge of coal from the Chinese, but there is no definite evidence to support this view. We do know, on the other hand, that the Greeks were aware of the combustible property of coal before the 2nd century B.C. Theophrastus of Eresus, for example, who died at Athens in 286 B.C., refers to " brittle stones . . . which become as it were burning coals when put into a fire, and continue so for a long time." Some of the stones are said by this writer to be black, smooth, and compact before use, but to become like pumice in the course of burning.

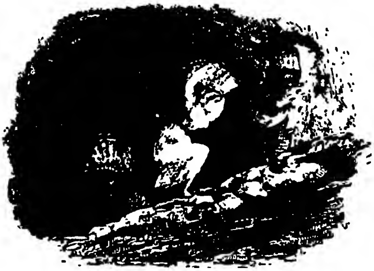
Coal was undoubtedly utilised extensively by the Romans during their occupation of Britain, but subsequent to their departure the practice of burning this fuel seems to have fallen into disuse. There is no mention of coal in Domesday, but by the beginning of the 13th century it was being dug on the southern shore of the Firth of Forth. About this time coal was obtained in the form of " pebbles " along the seashore bounding the Fife and Northumberland coalfields, which probably accounts for the origin of the name " sea-coal," by which it was known down to the 17th century.

Progress in the methods adopted for winning coal was very slow. Working of outcrops was followed by mining as early as the 14th century, though until well into the 17th century even the best pits were still only roughly timbered holes in the ground, the coal being raised in " corves " or baskets suspended by a rope from a windlass. The mouth of the pit and the windlass were covered by a thatched roof which afforded protection from rain and wind. The mines were often waterlogged and full of foul gases. About halfway through the 17th century improvements were devised by Beaumont and others, mechanical appliances for raising water were introduced, and wooden railways were laid at the surface. A very crude form of ventilation of shafts and workings also came into use.

We have told in Book II of the introduction of Savery's " fire-work " at the beginning of the 18th century, followed by the more effective engine invented by Newcomen. Newcomen's engine brought considerable areas of coal into the market which had previously been neglected as being unworkable. Mining received a marked impetus and some progress was made in methods of working. The flint and steel mill for underground illumination was invented by Spedding between 1730 and 1750. In 1761 a coal-cutting machine was invented, followed in 1768 by " Willie Brown's Iron Man." This was a machine operated by the bodily power of two miners. Lack of power supplies underground arrested further machine-cutting developments for a time, but early in the 19th century a new idea was utilised in a Yorkshire mine. A horse was harnessed inside a large frame. The floor formed part of an endless band, fitted with wooden slats and running on pulleys. When the horse tried to walk forward on to the band he remained stationary, the band travelling backwards and communicating its motion to a sprocket wheel. Links connected this wheel to a pick fastened on a swinging arm. Horse and machine were both urged forward as undercutting progressed, the machine being mounted on rails laid along the coal face. A similar method of obtaining motive power, though differing in detail and applied to other purposes, is illustrated in Agricola's *De Re Metallica.*

Many railways were laid down at British collieries between 1800 and 1820. Mechanical ventilators were first introduced at this time. One installed in 1807 was an exhausting air pump, consisting of a wooden piston 5 feet square with 8 feet stroke, working in a wooden chamber at twenty strokes a minute. It supplied 6,000 cubic feet of air a minute.

The safety lamp had come into existence by 1816 as the result of the work of Clanny, George Stephenson, and Sir Humphrey Davey.[1] Compressed air was first used at a British colliery about 1850, a date which marks the beginning of a new era in the application of power-driven machinery to colliery requirements.



Women Coal Bearers, A.D. 1829.

2

Present Methods of Coal Winning

Mining has been regarded until recently not only as a self-contained industry, but as an industry which could be carried on satisfactorily by a large number of entirely separate, competing, small-scale units. It is now becoming manifest that such views are no longer tenable. Yet the notion that enormous benefits might accrue if exploitation of a nation's coalfields was co-ordinated on scientific lines by some central directing authority is one which has hitherto received little encouragement. Still less enthusiasm has been shown for the idea that coal-winning should be considered primarily as a branch of a far larger industry, in which the winning, treatment, and utilisation of coal would be co-ordinated and carried on at the highest possible level of co-operative efficiency. To these larger aspects of our coal resources we shall return later.

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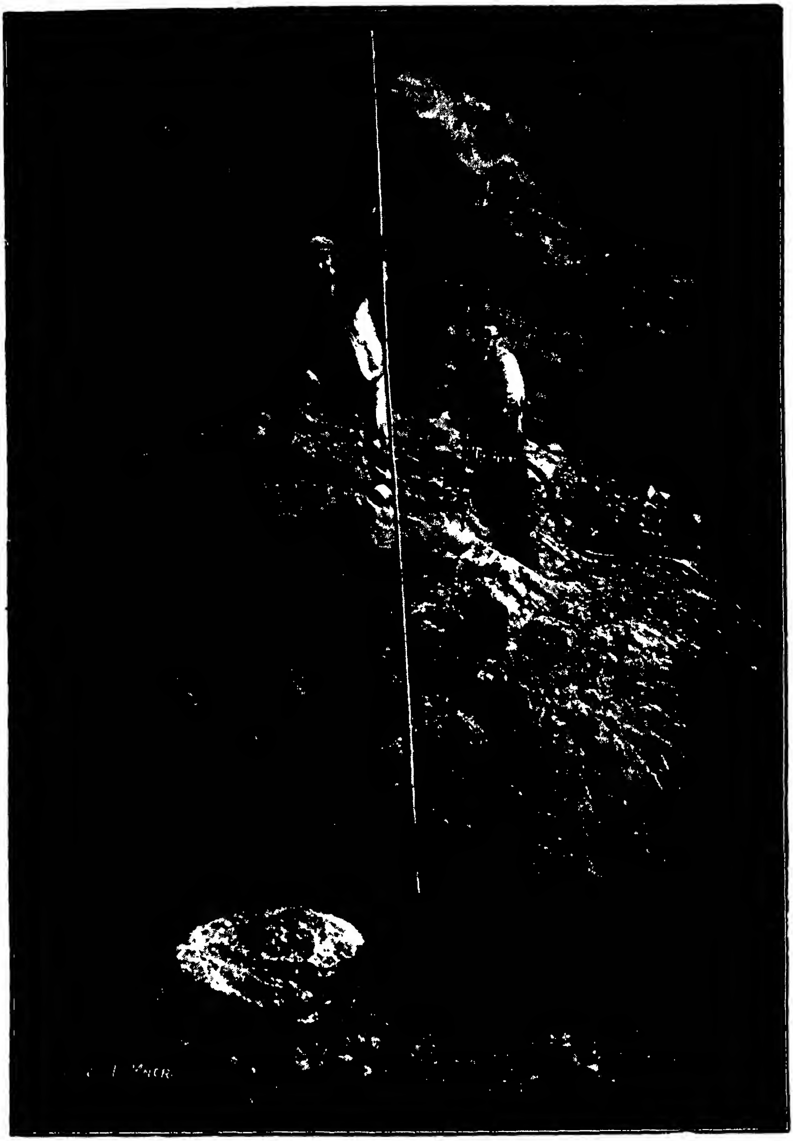
[1] See "Notes on the History of the Safety Lamp," by F. W. Hardwick and L. T. O'Shea, *Trans. Inst. Min. Eng.*, 51 (1915–16), p. 548.

Let us in the first place consider briefly the business of opening up and equipping a new colliery. It has been estimated that the present-day cost in Great Britain of laying out a colliery to be sunk to a depth of 800 yards, with not more than normal difficulties, would be approximately £1,900,000, made up as follows: sinking, equipment, and preliminary work underground, £750,000; wagons, £250,000; working capital, £150,000; houses, etc. (1,500 at £500 each), £750,000. It will be realised that by far the greater part of this expenditure must be incurred long before there is any prospect of putting coal on the market.

All work such as prospecting, boring, and drilling, shaft-sinking and lining, is now carried out with a degree of assurance and facility unknown to those responsible for such work a generation or so ago, in spite of the much wider range of knowledge now required. As a direct result of applying modern geological science to the search for coal, a number of very valuable deposits have been discovered which would certainly otherwise have remained unknown. Extensive study of the earth's crust, of the way in which it has been built up, folded over, or otherwise modified by subsequent upheavals or the deposits of a later age, now enables the mining engineer to advocate shaft-sinking under conditions which, in days gone by, would have presented insuperable difficulties.

Again, improved boring and drilling machinery has made much greater depths of operation possible in recent decades. Rather more than sixty years ago the rotary diamond drill first came into use in Great Britain. This apparatus consists essentially of a vertical tube which is given a rapid rotary motion. The lower edge of the tube has a number of diamonds bedded into its face, and upon the cutting action of these the effectiveness of the tool depends. A core is obtained and withdrawn from the borehole, examination of the cores indicating the nature of the underlying strata. More recently, successful use has been made of hardened steel shot in the place of diamonds for work of this nature. Though the general idea remains the same, such drills have now been greatly improved in detail. As an indication of the progress which has been



(*Courtesy of the " Iron and Coal Trades Review.*")

Exploring with a modern hammer drill. The drill held by the man on the left indicates the depth which can be reached.

[*To face p.* 24

made in core drilling, it may be mentioned that whereas the greatest depth attained in Great Britain sixty years ago did not exceed 600 feet, boreholes are now carried down to, and cores are obtained from, depths of over 6,000 feet.

Once the general lie, thickness and extent of a seam has been proved by prospecting, boring, the examination of cores, and so forth, and careful consideration has been given to special problems likely to be met with, such as underground accumulations of water and gas, or soft and unstable ground overlying the seam, the next step is to decide upon the number, position, and size of the shafts to be sunk. The placing of the main shaft will be affected by various considerations, each of which will have an important bearing upon the successful operation of the colliery. To begin with, it should be sunk in a position which will enable the seam to be worked from its lowest point. This will not only facilitate draining, but will also make for easier haulage. It is, moreover, manifestly desirable to place a shaft near the centre of the area to be worked. Finally, the question of haulage above ground, facilities for conveying the coal to railway, waterway or other means of reaching markets must be given due weight.

Shafts are usually circular, though rectangular shafts are still sometimes sunk in America. Following upon excavation, drilling, blasting, and other sinking operations, the shaft must be lined. Brickwork is commonly used for this purpose, though other types of lining, concrete for example, may be adopted, especially when sinking through wet ground. Such linings may be backed by liquid cement injections to strengthen them and render them watertight. The shaft is continued below the level of the workings, the lower portion being covered in and arranged to receive the water draining from the mine.

Assuming now that a shaft has been sunk and equipped with gear, and that all is ready for opening out a new colliery, consideration must next be given to the direction and construction of the various main haulage roads radiating from the pit bottom. Along these roads rails must be carefully laid, and at a suitable gradient in favour of the load. And so at last we reach the stage of actual production.

There are many methods of removing the coal from its bed, but, generally speaking, we may say that this is done either by dividing the coal into rectangular blocks, by driving passages chequer-wise through the seam ; or better, a long wall of coal is attacked, the face being gradually worked forwards into the seam, while the growing space behind the working is filled in with packing. As the work proceeds the roof is supported by timber or metal props.

In the " long wall " method of working, the seam is undercut along the face and temporarily supported by props or " sprags." Undercutting the seam by hand is an exceedingly arduous and dangerous task. When the sprags are removed, the mass of coal either falls by its own weight, or it may have to be driven down by the use of wedges or explosives.

And now at this stage, let us endeavour to visualise a modern colliery undertaking in its entirety. Here we have what is in effect a large, underground city, with many miles of " roads," any one of which may be several miles in length ; roads which perhaps run at different levels and link up with several shafts communicating with the outside world. At one such colliery in Belgium, the main shaft reaches a depth of 3,773 feet, a distance more than four and a half times the height of the Woolworth Building, New York, and ten times the height of St. Paul's Cathedral. The mechanical equipment of our colliery will consist of coal-cutting machinery, haulage arrangements below and above ground, winding engines and gear for lowering and raising men and materials, also ventilating and water-pumping plant. At the surface, in addition to transport and loading facilities, there will be apparatus for cleaning and grading the coal and possibly for carbonising some of it as well.

Visualising a colliery in this way, we see quite clearly that—apart from general lay-out, organisation and management—the paramount necessities for coal-winning are machinery and power. This being so, it is surprising to note that (at least in Great Britain) only in recent years has serious consideration been given to the desirability of installing really efficient power plant. With ample small coal available on the spot, colliery

(*Courtesy of Messrs. Walker Bros., Ltd.*)

A modern pit-head winding gear.

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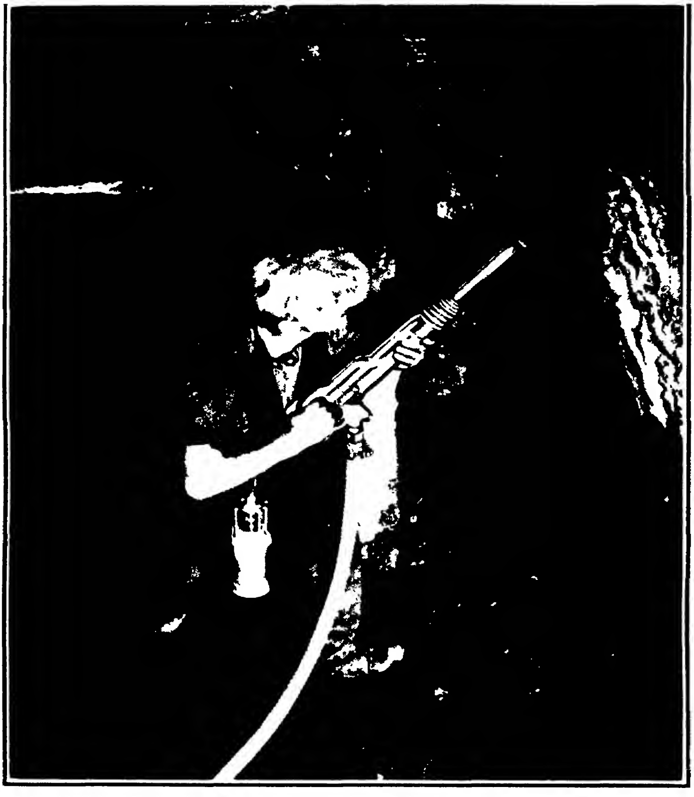

(*Courtesy of Messrs. Climax Rock Drill and Eng. Works, Ltd.*)

Coal miner using a pneumatic ripping pick.

leases which have permitted as much as 10 per cent. of the total output to be used at the colliery, and with relatively cheap unskilled labour, there has been in the past little inducement to instal highly efficient power plant, or to run as efficiently as possible such plant as was installed. A shorter working day, and higher wages for unskilled labour, however, have now made it very essential to effect economies wherever possible. This has led to widespread adoption of labour-saving machinery and the installation of centralised electric power plant, with a corresponding reduction in the number of unskilled and semi-skilled labourers employed about the mine. The adoption of intensive mining methods—extracting the largest possible output from the smallest possible area, instead of working several scattered areas—while reducing costs of haulage, upkeep, supervision and so forth, is also having the effect of cutting down the number of men required for a given output.

Where there is danger from accumulations of gas in a mine, compressed air may be conveniently used for power purposes, though the overall efficiency of this system, as we have pointed out elsewhere, is very low. Steady improvement in the design of electrical apparatus, and improved methods of installation, have eliminated many of the risks of explosion and shock, which in the past gave rise to a prejudice against the use of electricity. Electric power has so many advantages that practically all large collieries now use it for one purpose or another, while many use it wherever power can be conveniently applied above and below ground. No doubt less care is taken over electrical installations in some American mines than would be tolerated in Great Britain, too much reliance being placed on notices of which : " The last man who touched this wire in now in the cemetery," is typical. On the other hand, as the reader is probably aware, natural conditions in American mines are in general much more suited to the use of power-driven machinery underground than those which obtain in most British collieries ; while there can be no question that Americans have for long been more ready to take risks in the application of machinery and power to coal mining than have British owners and officials.[1] Underground electric haulage in particular has made great headway in the United States, where electric locomotives are widely used for this purpose, making it possible to eliminate the use of ponies in the pit and reducing the number of boys and youths employed underground ; also enabling the workmen to ride to and from the coal face, and providing facilities for the main haulage roads to be electrically lit throughout. Coal-cutting machines are extensively used on both sides of the Atlantic, though it may be noted that 80 per cent. of the total coal used in Britain is still cut by hand, leaving ample scope for further mechanisation. Indeed, more coal was being cut by electrically operated cutters in the United States twenty years ago than is cut by this means at the present time in Great Britain. It should be added, however, that coal-cutting machinery can only be employed profitably with seams exceeding 3 feet in thickness, and American coal seams in general have the great advantage of being much thicker than British seams.

Electric winding is now being adopted to an ever-increasing extent. Indeed, having regard to the almost universal trend in colliery equipment, it is impossible to avoid the conclusion that at no very distant date the majority of large colliery undertakings will be electrified throughout. This does not mean that all the problems and difficulties of mining will thereupon be eliminated. Far from it. Much colliery work must still be arduous, and will continue to involve risks. But it does mean that coal mining may now be considered as one of those industries which are moving definitely and unmistakably towards complete scientific organisation, operation and control. It is by no means the least of the manifold advantages of electric power that its use necessarily tends to eliminate the ignorant and the inept. The colliery of the future will depend not upon the bodily toil of unskilled and semi-skilled men, so much as upon the work of capable, scientifically trained officials, co-operating with intelligent craftsmen in the supervision and

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[1] This statement implies neither approval nor disapproval. So much depends on circumstances as well as outlook.

(*Courtesy of Messrs. Anderson, Boyes* & *Co., Ltd.*)

Cutting coal by machinery. Making a shearing cut.

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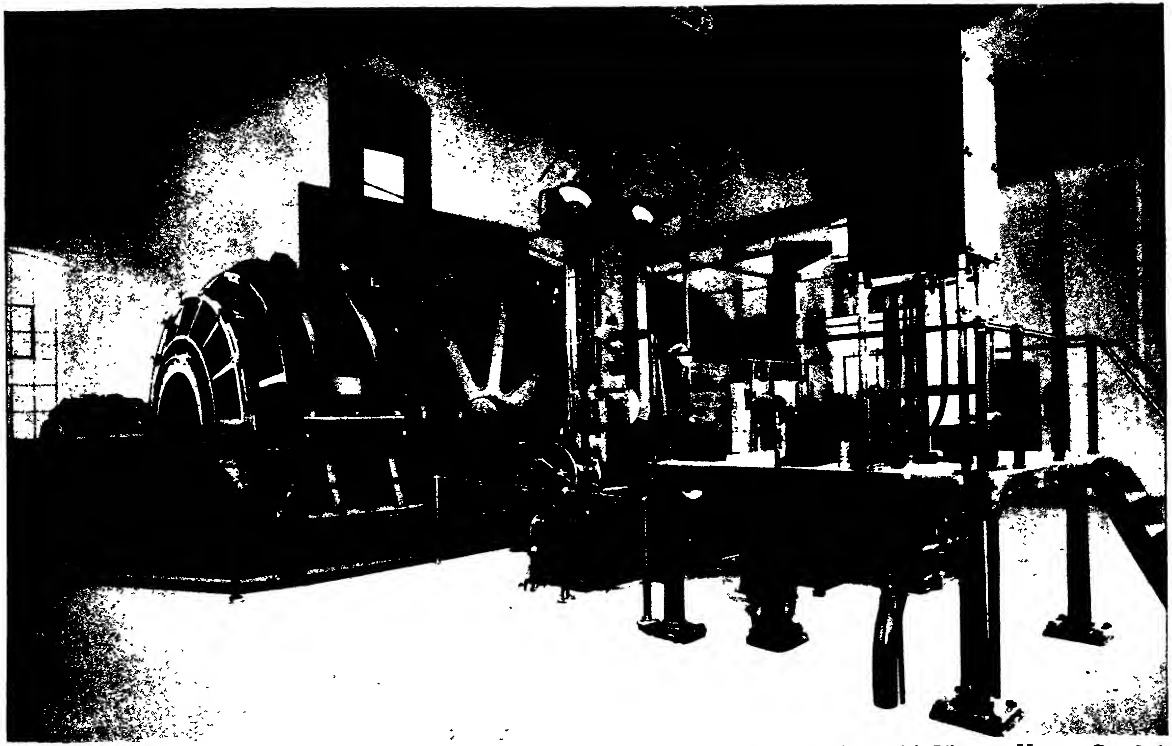

(Courtesy of the British Thomson-Houston Co., Ltd.

An electric winder at Thoresby Pit.

operation of highly complex, but efficient and enormously productive, power-operated machinery.

3

The Utilisation of Coal : Economy in Combustion

Having won our coal, the next step is to decide what we shall do with it. There are several varieties of coal, all of which may be burned, and most of which may be carbonised. Present methods of burning coal are still far from satisfactory. Complete combustion is very rare, and incomplete combustion results in the production of soot and smoke. So that quite apart from the loss of heat energy and waste of by-products involved, the burning of coal as commonly practised must be condemned on the grounds of atmospheric pollution. The extensive damage to property and danger to health traceable to this source are alone sufficient to justify the demand that wherever possible coal shall be carbonised rather than burnt.[1] It has been estimated that in Great Britain some two million tons of potential fuel in the form of soot and smoke escape annually from domestic fireplaces into the atmosphere, and about as much again from industrial chimneys. This is equal in weight to approximately five days' output of coal from British collieries, so that the work of over a million men is in effect devoted for five days a year to providing the soot and smoke which blot out the health-giving sunlight, react injuriously on the health of urban communities, and are the direct cause of heavy expenditure which would be materially reduced by the carbonisation of coal.

We shall discuss carbonisation in another section. Our purpose here will be to indicate the extent to which greater economy in combustion is now being secured. For no matter how desirable carbonisation may be, no matter how many people may be persuaded that the destruction of potential by-products and the emission of smoke is a definitely wasteful, anti-social act, it is impossible to effect far-reaching industrial changes suddenly. The burning of raw coal will therefore in all probability continue on a large scale for some time to come, possibly for another generation or so. What, then, is being done to ensure that the processes of combustion shall be carried on with the highest attainable efficiency?

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[1] The damage of coal combustion products to buildings is largely due to oxides of sulphur—a problem which is exercising the minds of fuel technologists in connection with super-power stations in London, Manchester and elsewhere. The controversy about the proposed Battersea power station is a case in point.

Let us note first of all that at present in Great Britain about four times, and in the United States about six times, as much coal is still being burnt as is carbonised before use. Of this more than half is accounted for by the demands of factory owners and domestic consumers. Again, rail transport accounts for an additional 25 per cent. in America and rather more than 13 per cent. in Great Britain. This means that despite rapid progress in recent years, only a small proportion of the whole is as yet consumed at electric power stations, so that there is still enormous scope for further industrial electrification. And since modern power station practice is representative of the highest efficiency in the burning of coal so far attained, it will be obvious that further progress in electrification is the surest road to large-scale economies in combustion.

Certainly if the light and power requirements of industrial and domestic coal-burning consumers were to be universally met by supplying them with electric energy from large central generating stations, many million tons of British and American coal would be saved every year. Some idea of economies which might be effected in this way can be obtained by turning to what has already been done. Thus, it is stated on excellent authority that if the energy supplied by the power stations of the United States to industry in 1927 had been generated within the factories themselves, at least 40,000,000 tons more coal would have been burned than was actually consumed.[1]

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[1] It will be perhaps as well to emphasise here that, despite its many advantages, the electrification of industry is no substitute for the *carbonisation* of coal. We have referred above to the production of light and power by electricity, but purposely refrained from including heat. For even under ideal conditions there is at present little prospect of electricity being used for more than a limited range

As for rail transport, the possible economies directly traceable to electrification extend far beyond the actual reduction in fuel consumed. Basing his calculations on extensive experience, Lieut.-Colonel E. O'Brien, formerly electrical engineer to the London, Midland and Scottish Railway, tells us that if the main lines of the four British railway groups were converted to electrical operation, then, excluding the cost of fuel on the one hand, and of electric energy on the other, a saving in operating expenses of no less than £21,000,000 a year could be achieved.

But this is not all. The benefits due to large-scale electrification are steadily increasing from year to year owing to constant progress in the design of electric power plant. Thus, in the six years from 1922 to 1927, the fuel consumption per unit generated in twenty-five of the most efficient stations in Great Britain was reduced by nearly 14 per cent. American statistics for the same period indicate equally remarkable results. Turning to the figures for 1927, for example, we find that in that year 2½ billion more kilowatt-hours of electricity were generated in the United States *with the use of* 150,000 *tons less fuel* than in 1926.

There is no need to weary the reader with further statistics. Enough has been said to indicate that large-scale electrification and economy in coal combustion are practically synonymous. No doubt much may yet be done—as much has already been done—to increase the efficiency of domestic coal-burning equipment. Greater care in grading and cleaning coal is another factor in economy which should not be overlooked. Hitherto thousands of tons of ash and dirt have been uselessly transported about the country and delivered to consumers. The provision of plant for separating this refuse from the coal at the colliery is clearly an important step towards the more scientific treatment of fuel; and in so far as it eliminates waste in transport of coal for burning purposes, may certainly be regarded as contributing to economy in combustion. Signi-

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of heating requirements. Coal gas is now, and seems likely to remain, a cheaper and more economical fuel for domestic heating and cooking, as also for a considerable range of highly important industrial processes.

ficant as these and other processes are, however, it is to increased electrification of industry that we must look for really notable economies where the burning of coal is concerned.

4

The Utilisation of Coal : Gas and its By-products

Many people still think of coal solely in terms of fuel, seeking at most to extract the largest possible amount of heat from it. Modern science, on the other hand, tells us that coal is not so much a fuel as a chemical resource. It is capable not only of meeting the world's requirements for light, heat, and power, but also of supplying us with numerous substances which are already considered to be essential to our comfort, convenience and well-being.

Of such substances, those derived from coal-tar—a by-product of gas and coke manufacture—is the most interesting as well as the most important. The extraordinary nature of this material may be gathered from the fact that it has been found to contain nearly 200 compounds. In addition, the synthetic chemist is able to build up many thousands of new substances out of the products actually extracted. In short, it is one of the most valuable additions to man's resources in materials that has ever been discovered. And when coal is burnt, all those treasures which might otherwise have been obtained from it are completely thrown away.

As is now widely known, the alternative to burning coal is to bake it in a closed retort or oven. Air is excluded from the retort so that the coal cannot burn even when it reaches a state of incandescence. Distillation—or carbonisation as it is often called—replaces combustion ; gas is liberated and a carbon residue, coke, is left behind in the retort. Tar and other by-products are at first held in suspension in the gas, and are therefore drawn off with it when the latter is pumped away from the retort through a connecting pipe. In actual practice there are usually a number of retorts, with their connecting pipes all leading away to one large gas main. The crude gas, after being pumped away, passes through a series of cleansing and purifying processes before it is fit for general consumption. From a gas-making point of view, the substances removed by these processes are " impurities "—tar, water of distillation charged with ammonia, sulphuretted hydrogen, and so forth. But it is from these so-called impurities that the valuable by-products, other than coke, are obtained.

The idea of carbonising coal is, of course, by no means new, and it will be interesting briefly to trace its origin and subsequent history. As long ago as 1609 a Dutchman, Van Helmont, found that coal when heated gave off an inflammable vapour, which he called gas. It was not until 1792, however, that practical use was made of the discovery. In that year William Murdock lit up his house at Redruth with the new illuminant.[1]

A native of Moravia called Winsor next appeared on the scene. In 1804 he took out a patent for " an improved oven, stove or apparatus for the purpose of extracting inflammable Air, Oil, Pitch, Tar and Acids from, and reducing into Coke and Charcoal all kinds of Fuel." At the same time he issued a pamphlet extolling the advantages of his " New Patent Coke."

If ever a man was fitted to advertise the value of a new idea it was Winsor. He was indefatigable in his efforts to enlist the support of influential business men, while the exuberance of his fancy in describing the possibilities of his patent knew no bounds.

> " The lighthouses on our coasts," said he, in one of his numerous pamphlets, " may be rendered like blazing stars to guide our seamen over the watery deep. . . . As to illuminations, they may be carried on to the utmost extent of beauty and variegated fancy by this docile flame, which will ply in all forms, submit to instant changes, ascend in columns to the clouds, descend in showers from

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[1] In 1795–96 Murdock operated a small experimental gas plant at Neath Abbey Ironworks, and in 1802–3 installed a plant for lighting the Soho Works, Birmingham, of Messrs. Boulton and Watt. In 1804 he lighted the cotton mills of Messrs. Phillips and Lee at Manchester with 900 burners ; also lighting the residence of Mr. G. A. Lee in the same city. He read a paper on the subject before the Royal Society on February 25th, 1808.

It has been claimed (see letter in *The Times*, June, 1924) that George Dixon, of Cockfield, Durham, had previously experimented with gas lighting about 1760.

trees, walls, etc., arise from the water, and even in the same pipe with a playing fountain."

By 1807 Winsor was installed in offices in Pall Mall on the site now occupied by the Carlton Club. Here he continued his propaganda, fighting valiantly against old-established customs and prejudices and much doleful prophesy of the "Evils that must inevitably result from the Introduction of Gas Lights." Typical of the ridicule to which he was subjected was the remark made by Sir Walter Scott: "There is a madman proposing to light London with—what do you think? Why, with smoke!" Napoleon, too, spoke scornfully of such schemes, dismissing the idea of gas lighting as "une grande folie." Nevertheless, Pall Mall was successfully lighted by gas on January 28th, 1807, and in April, 1812, a charter was granted by Parliament to Winsor's company—"The London and Westminster Gas Light and Coke Company," as it was then called—and the manufacture of gas thereafter became a practical commercial proposition. Other companies to exploit the process were soon formed, and in 1816 the necessary plant was installed at Baltimore, the first city in the United States to adopt gas lighting. Paris followed suit in 1820.[1]

The earliest recorded instance of gas having been used for domestic cooking dates back to about 1830. The use of coal gas on a large scale for industrial heating is a comparatively recent development. Great headway has been made in this regard during the past ten years or so, so that now it is estimated that there are some 20,000 different uses for gas in industry. Many interesting details will be found in a paper on "The Use of Town's Gas in Industry," read by Sir Arthur Duckham at the First World Power Conference in 1924. Indicative of the expansion of gas manufacture in general is the fact that in Great Britain there are now more than 40,000 miles, and in the United States 90,000 miles, of gas mains, not counting the

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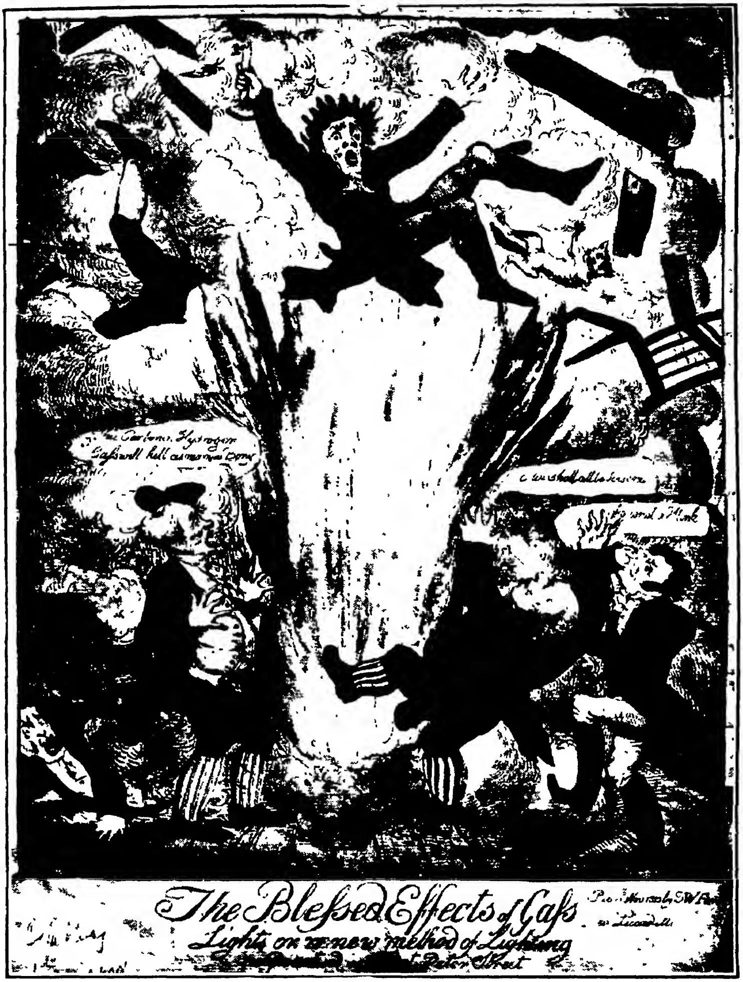
[1] For details of the plant and processes employed for generating, purifying, and burning gas in those days, see: *Description of the Process of Manufacturing Coal Gas now Employed at the Gas Works in London*, by Frederick Accum, Operative Chemist, London, 1819.

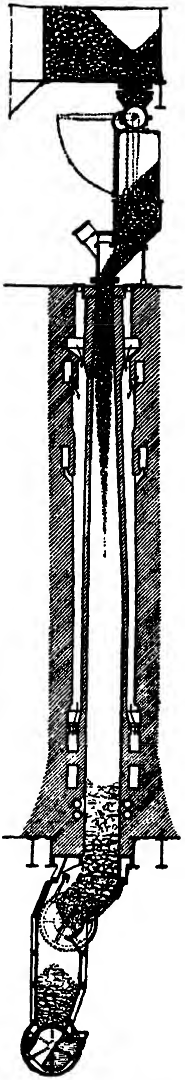

Carbonic Hydrogen
Gas will kill as many as Boney
The Bleſsed Effects of Gaſs
Lights on a new method of Lighting

(*Courtesy of the British Commercial Gas Association.*)

An old cartoon illustrating the public apprehension when gas lighting was first introduced.

many thousands of miles of pipes linking these mains to houses and factories.

In the early days of town gas manufacture, retorts were made of cast iron. Modern methods date from the introduction of retorts made of fireclay, which soon completely replaced those made of iron. Fireclay retorts will stand much greater heat than iron, and, though having little cohesive strength, possess the advantages of great strength under compression, and of expanding under heat equally with brickwork, so that they can be built solidly into brick settings, thus compensating for their lack of cohesion. For many years the retorts were filled and discharged entirely by means of hand stoking. The elimination of drudgery in a modern gas works retort house, however, is just as notable as in the boiler house of a modern electric power station. The old hand-stoking methods for horizontal retorts have now been superseded by mechanical stoking, the most efficient type of machinery for this purpose being operated electrically. One of the advantages of vertical retorts is that stoking is eliminated altogether, the materials travelling in and out under gravity.



Section of Woodall-Duckham continuous vertical gas retort.

The invention in 1885 of the incandescent gas mantle by Ritter von Welsbach completely revolutionised the older methods of obtaining light from gas. The gas engineer had till then concentrated his efforts upon the illuminating qualities of gas. Thereafter he was enabled to remove from the gas most of the constituents upon which its illuminating power had depended. For the light given off by a gas mantle depends wholly upon the highly refractory substance of which it consists being heated by a non-luminous Bunsen flame.

Gas engineers also found that a much wider range in methods of carbonisation was available for them to choose from, thereby enabling them to produce considerably more gas from each ton of coal carbonised, also freeing them to take greater advantage of the by-product possibilities of gas manufacture. An increased yield of gas has been secured in many works by passing steam through the coke residue in vertical retorts. The steam is decomposed into hydrogen and oxygen as it passes through the hot coke (carbon), and carbon monoxide is formed. The mixture of carbon monoxide with hydrogen gas makes a valuable addition to the coal gas evolved by the carbonisation. The proportion of " water-gas " (as it is called) in public gas supplies in Great Britain is usually about 20 per cent. In the United States about 75 per cent. of the total amount manufactured is " carburetted water-gas " ; that is, water-gas enriched by hydrocarbons derived from oil. A certain amount of carburetted water-gas is manufactured in Great Britain also, a number of the larger works having installed plant specially designed for this purpose.[1]

It is perhaps desirable to repeat that not all coal is suitable for carbonisation. Though coals in general contain carbon, hydrogen, oxygen, nitrogen, and ash, the proportions vary considerably according to the particular type of coal under consideration. Heating properties are primarily dependent upon the percentage of carbon. Anthracite normally consists of over 90 per cent. carbon, and is, therefore, a fuel of the highest order where an intense, localised heat is required. It burns without either flame or smoke. It is bituminous coal, which, containing less carbon and a larger proportion of hydrogen, nitrogen, and oxygen, gives off gas and supplies us with valuable by-products when heated in a retort. Brown coal, or lignite, of which there are vast quantities in various

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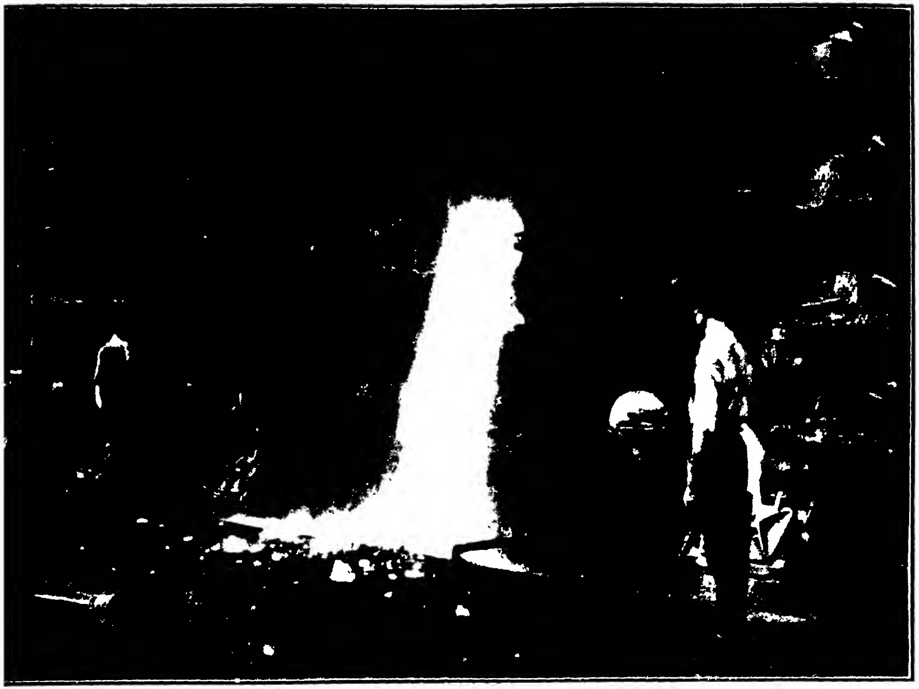
[1] The reaction of steam on incandescent carbon was first noted by Fontana in 1780. From 1856 to 1865 the town of Narbonne was lit by platinum wire rendered incandescent by water gas. The first really practical developments, however, were due to Lowe, Strong, and others in the United States from 1873 onwards.



(Courtesy of the British Commercial Gas Association.)

Taking red-hot coke from horizontal gas retorts.

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parts of the world, can also be carbonised after suitable treatment.

Modern British practice in high temperature gasworks carbonisation results in a yield from a ton of a suitable gas coal of about 12,500 cubic feet of gas, 13.5 cwt. of coke (containing ash), and 10 gallons of tar. Of the coke about 2 cwt. are consumed in carbonising the coal, leaving about 11.5 cwt. for outside consumption. The thermal efficiency of the carbonisation process is from 75 to 80 per cent.

All the products of carbonisation except gas have been considered as necessary nuisances at one period or another. The coke is still a problem. From the other items are now derived valuable materials, among the most important of which are ammonia (fertiliser), benzols, phenols, creosote, and tars, from which synthetic dyes, drugs, disinfectants and other commodities are made. Prussian blue should also be mentioned, and pitch. It is of interest to note that the remarkable work done by Ehrlich and others in recent years in combating the minute protozoan parasites responsible for some of the most terrible diseases by which mankind is inflicted, such as syphilis, sleeping sickness, and yellow fever, has been based upon the use of drugs derived from coal tar.

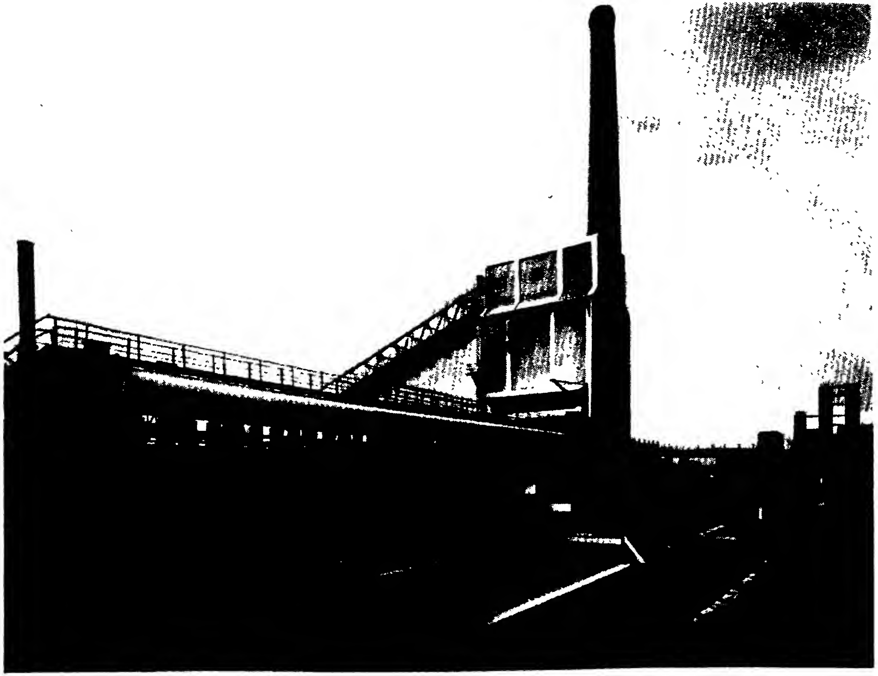
Gasworks coke, once it is lit, makes an excellent fire, but it is less easy to ignite than coal when used in the ordinary domestic grate. Combustion, moreover, is adversely affected by contact with the metal parts of a fireplace. These difficulties are, however, being rapidly overcome, partly by the production of a coke containing about 5 per cent. volatile matter, and partly by specially designed grates, lined throughout with firebrick and incorporating other features calculated to promote combustion.

There is, of course, a coke with rather different characteristics—harder and less friable—produced by what is known as the coke-oven process and used for metallurgical purposes. In coke-oven procedure coke is the main objective, while the gas produced is a by-product. Coke is the principal fuel used in blast furnaces for converting iron ore into pig iron, a process details of which are given in a later chapter. A metallurgical coke was produced from early in the 19th century and onwards in mound or beehive-shaped ovens—the shape previously adopted when charcoal was the only fuel available—and in the process all the by-products were destroyed. By-product coke ovens first made their appearance about 1880, but nearly another quarter of a century passed before prejudice against the coke at first produced in this way was overcome.

After its inception on the Continent (principally in Belgium and Germany) and subsequent introduction into Great Britain, the industry made considerable progress in the United States. American engineers introduced new features into coke-oven design, narrowing the oven while increasing the height and length, and adopting the use of silica walls. In this way capacity and output have both been increased, and the silica oven is now widely used on this side of the Atlantic as well.

There appears to be a reasonable prospect at last of the gas resulting from the production of metallurgical coke being dealt with on scientific lines. Such gas is in some plants still entirely wasted, and in others is used for heating the coke ovens, although a poorer and cheaper gas would be quite good enough for this purpose. Proposals have been made to transmit the gas through a " grid " of mains linking up with the gasworks of neighbouring towns, and some progress on these lines has been made in this country in the Sheffield district. In Germany extensive pioneer work in long-distance gas transmission has been undertaken, the mains for this purpose being already over 100 miles in length. It may be added, however, on the authority of Sir David Milne-Watson (Presidential Address to the Institute of Fuel, October, 1929), that the amount of coke-oven gas used for town purposes in Great Britain exceeds that so distributed by the German long-distance gas scheme.

We cannot close this section without commenting upon the remarkable progress made by the gas industry in recent decades. When electricity first came into general use, there were those who jumped to the conclusion that gas would speedily become a thing of the past. The use of gas is, on the contrary, more widespread to-day than ever before, and the industry—thanks largely to the energy, enterprise, and public



(Courtesy of Messrs. The Woodall-Duckham Co.

Becker coke ovens at Bedwas, South Wales.

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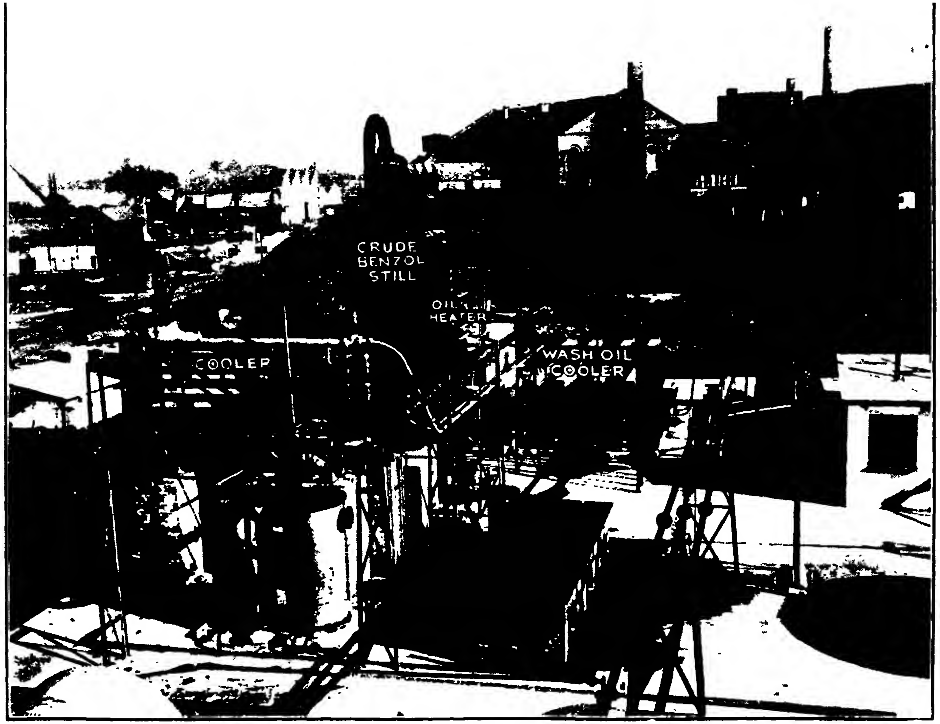
CRUDE
BENZOL
STILL
OIL HEATER
WASH OIL COOLER
COOLER

(*Courtesy of the British Commercial Gas Association.*)

Benzol recovery plant at a large gas works.

[*To face p.* 261

spirit of its officials—has undoubtedly a long and prosperous future ahead of it.

5

Recent Developments in the Treatment of Coal

We have seen that science is gradually permeating at least some of the activities involved in the winning and utilisation of coal. Nevertheless, no general plan of action has yet been adopted which is at once scientific, comprehensive, and on a scale commensurate with what we now know to be the potentialities of this remarkable material. Indeed, no such scheme can even be formulated until we resolutely refuse any longer to contemplate coal, gas, coke, tar derivatives, and the production of light, heat, and power as being the special preserves of separate, competing, inco-ordinated industries.

The need for a wider, all-embracing outlook in regard to these matters becomes even more apparent when we consider some of the novel methods of treating coal which have been applied with varying degrees of success in recent years. Among the most important of these are hydrogenation, low temperature carbonisation, and pulverisation.

Briefly, hydrogenation involves submitting coal—in powdered form and mixed with oil—to the action of hydrogen under conditions of moderate temperature and high pressure. It is probable that the most serious obstacle to fuller and wider exploitation of this process is the relatively high price of hydrogen ; over 20,000 cubic feet of this gas being necessary for the treatment of a ton of coal. But a survey of recent progress in the production of hydrogen indicates that there is a prospect of materially reducing this element of expense, so that the liquefaction of coal may very well be carried out on a far larger scale in the near future.

Much publicity has been given in recent years to another process, low temperature carbonisation.[1] We say " process," but there are in fact upwards of 100 low-temperature carbonisation processes now being experimented with in various parts of the world. In Great Britain alone there are some forty processes under consideration, and new companies are constantly being formed to exploit them.

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[1] Thomas Parker, of Wolverhampton, was the first to produce and patent a smokeless fuel by a process of low-temperature carbonisation. His patent is dated June 22nd, 1906.

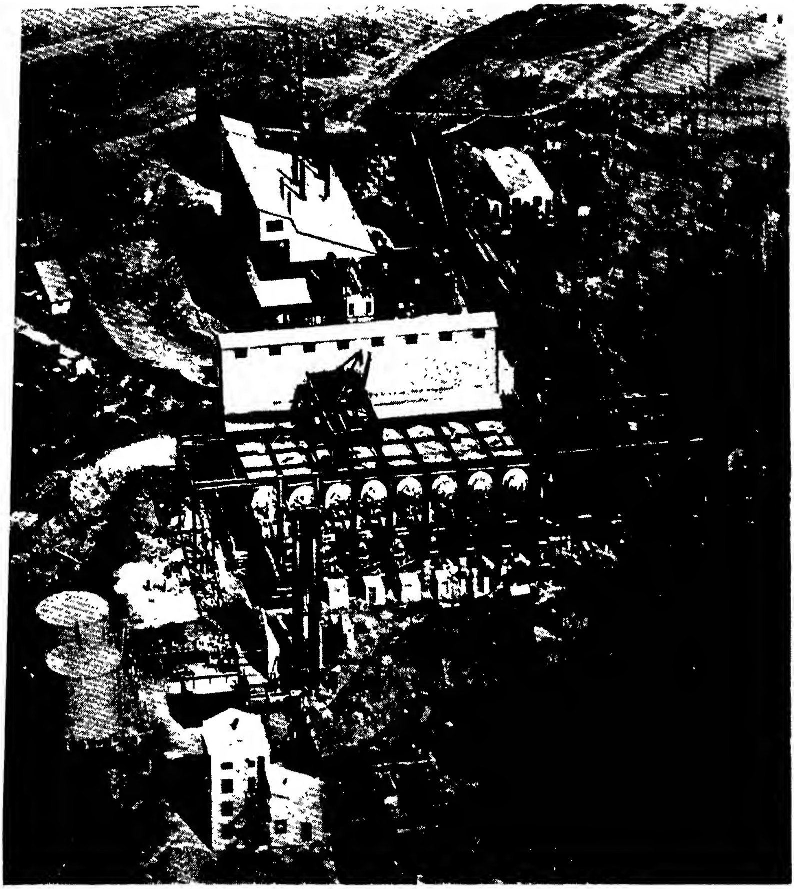
In a memorandum furnished to the Royal Commission on the Coal Industry (1925) Dr. Lander defines low temperature carbonisation as

> " the destructive distillation of coal at temperatures round about 600° C. instead of at the higher temperatures of 1,000° C. and upwards used in the gas and coke-oven industries. At the higher temperatures more of the coal is converted into gas and less into tar and coke, while from suitable coal a stronger coke is left behind ; incidentally the yield of ammonia is also much greater. At the lower temperatures enough combustible volatiles are retained in the coke to enable it to catch fire and burn steadily, though not enough to generate smoke. Large quantities of tar are collected without being decomposed into gas, whilst both from the gas itself and from the tar some light spirit can be extracted and converted into motor spirit. Low temperature carbonisation accordingly offers a possible means of so treating coal as to obtain at once a source of oil fuel and motor spirit, and a solid smokeless fuel that can be burned on any domestic grate."

Methods and results in low-temperature carbonisation vary as in other processes. A typical yield from 1 ton of coal containing 25 to 35 per cent. volatile matter would be from 3,500 to 5,000 cubic feet of gas of 800 British Thermal Units a cubic foot, 3 gallons of light oil, 15 to 20 gallons of low-temperature tar, and 14 cwt. of smokeless fuel containing from 10 to 11 per cent. volatile matter.

Despite boundless optimism displayed by many who are closely associated with low-temperature carbonisation, and an almost equally boundless literature on the subject, it cannot be maintained that this process has yet reached a stage at which it can be regarded as a fully developed industry. A great deal of further research and practical experience is required to ensure continuously satisfactory results from a wide range of coals.

Although the idea of pulverising coal before burning it dates



(*Courtesy of "World Power."*)

Low temperature carbonisation plant, New Jersey, U.S.A.

back at least forty years, it is only during the past ten years or so that it has become a firmly established method of treating coal for industrial combustion. The fuel is pulverised to the consistency of fine flour and then fed to the boilers by compressed air. This system of burning coal has many advantages, among which may be enumerated the ability to burn efficiently any grade of coal and extract from it the greatest possible number of heat units; increased flexibility in the working of steam boilers; greater cleanliness in the boiler house; better hygienic conditions for the attendants; and greatly reduced requirements in the amount of attendance necessary. The ability to utilise low-grade fuels—peat, lignite, anthracite, and pit washings, and coals with as high an ash content as 40 per cent.—is of special significance, since even if all medium and high-grade coals were to be carbonised, there would still be ample scope for the pulverising process. Here we may record the fact that pulverising also plays an important part in the manufacture of both black coal and lignite briquettes, although much of the coal used is already in the form of dust when it comes from the colliery. Briquetting is a process of some significance in relation to coal mining, since it provides an outlet for coal and anthracite dust which otherwise would be very difficult to sell, and, by accumulating at the collieries, would also be a serious obstacle to further mining operations.

The several methods of treating and utilising coal referred to above, as well as the older methods discussed in previous sections, cover a variety of quite different objectives. Here the main end in view is a maximum production of gas; there the manufacture of metallurgical coke; or, again, it may be the development of a smokeless fuel suitable for domestic use; or, as in another case, the conversion of coal into a liquid fuel. The very diversity of the products which may be obtained from coal makes co-ordination of the processes involved an urgent necessity if the waste due to conflicting purposes is to be avoided. But there is another highly important reason for scientific co-ordination. For once industries such as those we are considering achieve unity of purpose, they become to that extent a single industry. And an industry with a wide range of products, catering for widely different markets, is assured of a stability in composite demand presenting a striking contrast to the disastrous fluctuations which afflict those whose interests are restricted to the marketing of one or two products only. Having regard not only to this, but also to the many other considerations which lead inevitably to the same conclusion, it is not too much to say that there is no practical alternative to complete, though gradual, consolidation of the whole of the industries associated with the winning, treatment and utilisation of coal. In that way—and in that way alone—can such industries be assured of continuing prosperity, and coal become a permanent source of economic strength to the civilisation which materially is largely based upon it.[1]

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[1] It should scarcely be necessary to emphasise that what we have in mind here is a desirable *trend*, not something that can be accomplished—as by waving a wand—either in a year or two, or even in several decades.

CHAPTER II

OIL AND ALCOHOL

I

The Significance of Oil

Oil is the name applied to a number of bodies obtained from widely different sources, and varying considerably in physical properties and chemical characteristics. Such bodies may be derived directly from animal or vegetable origins, or they may be obtained from the earth, whence they flow under natural pressure, or alternatively may have to be raised to the surface by pumping. It is probable, but not certain, that oil derived from the earth—commonly called rock or mineral oil—owes its existence to the decomposition, at some far distant period of the world's history, of organic remains.

Whatever their origin, it is characteristic of all oils that they consist largely, and in some cases entirely, of hydrocarbons, and are without exception easy to ignite. They are also for the most part insoluble in water though they dissolve more readily in boiling alcohol, and are altogether soluble in chloroform, benzol, ether, and bisulphide of carbon. Their significance lies in the extraordinarily wide range of human requirements which they meet in their various forms of waxes, tallows, fats, and fluids, and the various products derived from them.

It would be quite impossible to give here a complete list of the uses to which oils and their products are applied, though it may serve to indicate the range of such uses if we mention that they not only play a *rôle* of the highest importance as a food, but also in one form or another are used in the manufacture of perfumes, flavours, medicines, lubricants, illuminants, fuels, leather and fibre dressings, candles, pomades, paint, varnish, soap, and road-dressing materials. In this chapter we shall confine our attention to mineral oil; the substance which, in addition to meeting a variety of general industrial needs, has within living memory wrought the most remarkable changes in our methods of transport by land and sea, made flying possible, and provided us with an entirely new source of power for manufacturing and allied purposes.

Mineral oil was in all probability known and used, for one purpose or another, many centuries before the possibilities of coal as a fuel were realised. Oil abounds in close proximity to regions once occupied by some of the earliest known civilisations. Attention must have been drawn at a very early date to the mysterious undying fires which burned with spectacular effect in various parts of the world—notably in the Near East, where such fires figured largely at a later date in the religious ceremonial of the followers of Zoroaster. Among ancient writers, Job refers to the rock pouring out rivers of oil, while both Diodorus Siculus and Pliny make unmistakable references to mineral oil and various closely related substances such as pitch and bitumen. Herodotus describes what seems to have been the beginnings of a petroleum industry not far from Susa in Persia; while Dioscorides, a Greek physician of the 1st century, A. D. gives particulars of a crude process of distillation used for separating one grade of oil from another.[1]

But apart from a limited consumption as an illuminant, in lamps which were little more than open dishes, and a perhaps wider but still restricted use as a medicine, many centuries elapsed before mineral oil began to play a part of any real importance. Then suddenly the whole world began to wake up to its potentialities, a wild scramble for oil followed which could only be parallelled by the gold rushes of earlier days, and in a few decades the commodity leaped from obscurity into a position of quite astounding significance in the affairs of mankind.

The beginning of a new era in the history of oil-burning was the invention in 1784 of a novel type of lamp by a Frenchman, Aimé Argand.[2] Yet even as late as 1850 the majority

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[1] The following references are of interest: Diodorus Siculus, II, 1; XXXI, 39; Herodotus, VI, 119; Dioscorides, I, 83–101; Ammianus Marcellinus, XXIII, 6, 16; Strabo, XVI, I, 15.

[2] Argand's reason subsequently gave way under a series of misfortunes, an he devoted the remainder of his days to an attempt to discover the elixir of life.

(*Courtesy of Messrs. the Anglo-Persian Oil Co., Ltd.*)

Ancient temple of Masjid-i-Sulaiman. The smoke is from a near-by oil well ; oil and gas being burnt until the well is harnessed.

[*To face p.* 2

of homes knew no better illuminants than the old saucer-like lamp and the tallow dip. Then experiments were made in distilling oil from coal and oil-bearing shales, a much improved lamp designed to burn lighter and more fluid oils was invented by a German called Stohwasser, natural deposits of oil began to be exploited, and the demand increased by leaps and bounds. Indeed, since no way of securing the now valuable fluid was known other than collecting it from springs and pools, demand very soon outran supply. Then digging and drilling was commenced in Pennsylvania by Edwin L. Drake, who " struck oil " by this process on the 23rd of August, 1859.

From such beginnings has grown—in the relatively brief period of seventy years—the vast industry which is now responsible for a world production of over 165,000,000 metric tons a year. To-day this mighty and ever-increasing flood of oil finds its way into countless engines and oil-burning furnaces throughout the world. Though oil is one of the newest of the great industries, there is none which contributes more effectively to the requirements of a civilisation based on machinery and power. We shall now briefly examine the highly interesting processes by which mineral oil is won, refined, and otherwise prepared for industrial consumption.

2

From Well to Refinery

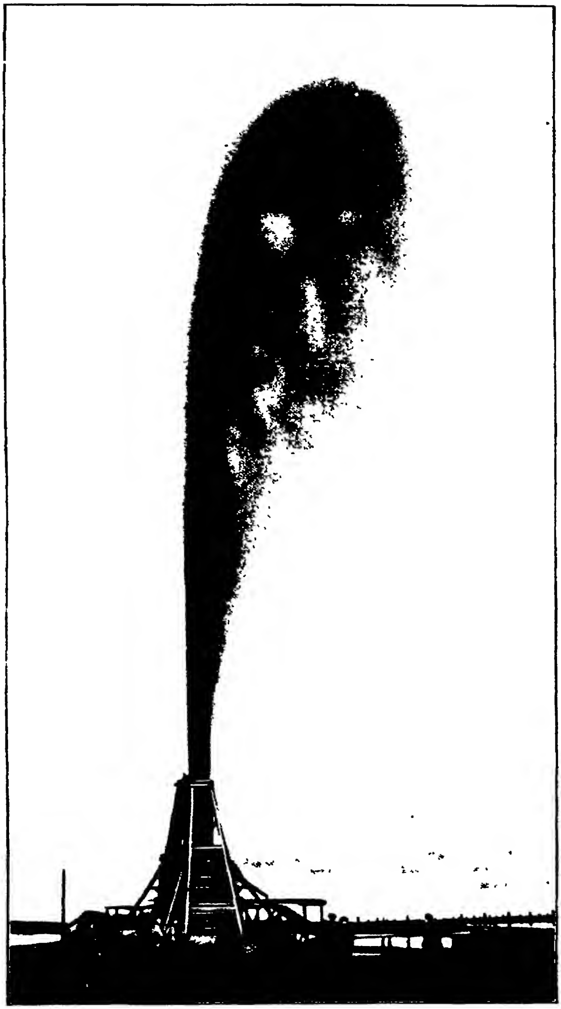
In the short period which has elapsed since the birth of the modern oil industry, an imposing amount of scientific knowledge has been brought to bear on the numerous problems which it has been found necessary to solve.

Gone, for example, are the old days of " wild cat " prospecting. The prospector of to-day is not only a man who has had a thorough training in physical science, but usually also has a specialised staff available for consultation when required. The fact is that attempts to locate supplies merely by looking for surface seepages of oil or gas can only lead to disappointment in the long run. Sinking a well may cost £20,000 or more, and such an expenditure can only be justified after the most exhaustive examination has been made of the geological and topographical indications of a selected site. Not only must a careful survey of the surface be made, but information relating to underground conditions must be deduced from strata exposed in cliffs, river beds and other likely places. Extremely delicate and sensitive instruments are then used to amplify the evidence thus obtained. Electric currents are made to flow through the earth between two electrodes sunk in the soil, and an area of bad conductivity will make itself manifest in the readings of the instruments in circuit with the current. Oil-saturated sand is well known to be a bad conductor, and its presence can therefore be detected in this way with a considerable degree of assurance by an experienced prospector.

Other methods are also adopted, one of which involves the making of magnetic surveys, and another the measurement of earth tremors, by means of which considerable knowledge of underground structure can be obtained. Some idea of the extraordinary precision of the instruments used in such work may be gathered from the fact that the ultramicrometer, used for earth tremor measurement, is capable of registering a movement of one-eighth of a millionth of a centimetre, or one-twentieth of a millionth of an inch.

Let us assume that a likely spot has been located. A timber or steel structure called a derrick is then erected over it. From this structure are suspended the boring tools, which may be either of the percussion or the rotary type, according to the character of the rock to be drilled. The percussion tool simply pounds its way through the rock. The rotary system resembles that adopted when prospecting for coal. A special cutting tool is used which works its way down very much as a gimlet bores its way through a piece of wood. A stream of liquid mud is pumped down the drill hole by means of a " sands " pump, lubricating the tool and washing out the cuttings and sediment which would otherwise accumulate and impede progress.

On reaching a supply the oil may rise under natural pressure. On the other hand it may not. Frequently it happens that



(*Courtesy of the A.E.G.*)

A spouting oil well.

[*To face p. 269*

either the flow is excessive, or, alternatively, it may have to be assisted by forcing gas down the well pipe under pressure. Excessive flow must be held in check by means of well-head fittings of sufficiently substantial design to withstand the heavy pressure to which they may be subjected. Through these fittings the well is connected to the pipe line which is now almost universally adopted for conveying the oil to the refinery ; a method which is of course a very great advance on the old wasteful and costly practice of transporting it in barrels.

Where wells flow under their own pressure, a very large volume of natural gas of high calorific value is given off from the oil, and the utilisation of this enormous potential source of power presents a difficult problem. In America large quantities have been distributed from the oil fields and delivered to industrial domestic consumers, sometimes several hundred miles away. Many oil fields in other parts of the world, however, are situated in thinly populated regions, where no other industries exist to consume the vast amount of surplus energy available. During recent years great progress has been made in the extraction of light gasolene and other valuable products, but so far no economic process has been devised which succeeds in turning to account the main bulk of the gas produced. This is at present ignited in great flares, thereby at least preventing the poisonous fumes given off by it from injuring the health of those who live and work in the district. In the oil fields of Persia, for example, no less than 25,000,000 cubic feet of gas a day are produced and treated, and 6,000 tons of gasolene are recovered every month. After treatment, some of the residue gas is taken through mains to provide a local gas supply, and the boilers at the power and pumping stations are also fired with it. But until science has revealed some new avenue of approach to this problem the remainder must still be burnt uselessly ; for though it is safe to say that no industrial undertaking in the world guides its activities more wholeheartedly by the light of science than the Anglo-Persian Oil Company, this waste of gas continues and will continue until some better means can be found for disposing of it.

From the wells the crude oil is taken to storage tanks and from thence is pumped to the refinery. Owing to the viscosity of the fluid, and to friction in the pipes, the pressure falls, and pumping must therefore be done in a series of relay-stations when the oil has to be conveyed for any considerable distance. In the case of the Persian oil fields the refinery is some 135 miles away at Abadan; the pipe line traversing mile after mile of hill and desert, and crossing two ridges, each of which is more than 1,300 feet above sea level.

Coming now to the refinery, the crude oil as it is delivered must be regarded as a complex mixture of many compounds. It is also the raw material from which many other compounds can be built up. The products derivable from crude oil may be classified according to their volatility. In the process of distillation the lighter, more volatile, constituents pass off as vapour at lower temperatures than those which are heavier. They are in this way separated into "fractions," although it should be understood that actually there is no sharply defined dividing line between one fraction and another. Refining involves the separation of these fractions by distillation; the products then being chemically treated to remove impurities. The still is merely a boiler with a space at the top which confines the vapour given off. From there the vapour is led away through pipes; condensation into the liquid state being usually assisted by water-cooling. In the course of distillation the most volatile fractions, which form the basis of petrol and kerosene, are first separated; then the others in order of their volatility as fuel oil, lubricating oil, paraffin wax, and so on.

After the distillate from the crude oil has been washed and partly deodorised in a solution of caustic soda, it is split up into fractions, one of the most important of which is petrol. The petrol at this stage is not that which is known to the motoring public, but still contains various impurities, notably sulphur. It is therefore passed through a final refinery process, involving agitation with a solution prepared by electrolysis, and emerges as a clear spirit ready for the market.

The processes for dealing with the heavy residue from the crude oil are particularly interesting. The heavier part of this residue, containing solid paraffin and lubricating oils, is

(*Courtesy of Messrs. the Anglo-Persian Oil Co., Ltd.*)

Laying oil pipes across the desert.

To face p. 270.

refrigerated. When the desired reduction in temperature has been obtained, the frozen oil is pumped under pressure through filter presses, where the solid paraffin is deposited while the filtrate containing the lubricants exudes through cloths. On removal from the presses the crude paraffin undergoes a whitening process, after which it passes on to the stage in which the last traces of colour are removed. The filtrate from the paraffin extraction plant is split up by distillation into various grades of lubricating oil, each of which receives its appropriate finishing treatment, either by the use of chemicals or by filtration.

3

Possibilities of Industrial and Power Alcohol

The ever-growing demand for light motor fuel has greatly stimulated the endeavour to find alternative sources of supply. It is true that the production of petrol has been considerably augmented in recent years by the use of improved plant and the adoption of new ideas. Distillation under pressure, for example—technically known as "cracking"—has made it possible to obtain from one barrel of crude oil nearly as much petrol as formerly was obtained from two. Output has also been increased by the recovery of spirit from natural gas. Nevertheless, the fear expressed in some quarters that there may be a petrol famine within the next ten years is not entirely without foundation. The multiplication of automobiles threatens to outrun the ability of the world's refineries to supply the necessary fuel.

We have already referred to the possibilities of obtaining motor spirit from coal. A further source of supply, as yet only beginning to be tapped, is the liquid fuel to be derived from oil shales, of which there are enormous deposits in various parts of the world. In Tasmania, for example, there are, according to geological surveys, at least 43,000,000 tons of shale, which it is estimated will yield as a minimum 1,720,000,000 gallons of oil. Again, when endeavouring to see ahead in this matter of supplies we must not overlook the fact, to which reference was made in Book II., that engines which will run on crude oil are now being developed for automobiles and aircraft. And yet another promising development of recent years is the use of alcohol for power purposes.

The term alcohol covers a number of substances which are closely related in the sense that they have many characteristics in common. They likewise differ in certain respects, and so chemists find it necessary to provide each with a distinguishing name, while at the same time expressing recognition of general resemblances. This is done by using in addition to the generic name " alcohol " such additional names as methyl, ethyl, propyl and others likewise ending in " yl." Each is built up of carbon, hydrogen, and oxygen, but in different proportions. Those with which we are primarily concerned are ethyl alcohol and methyl alcohol ; bodies which bear very simple relations to the hydrocarbons ethane and methane, differing from them chemically only by the addition of one atom of oxygen per molecule in each case. When the term alcohol is used by itself, it is generally understood that reference is made to ethyl alcohol, or " spirits of wine " as it is also called. Methyl alcohol is perhaps more widely known as " wood spirit," being at present largely obtained by the distillation of wood. It is also jocularly referred to in certain parts of America as " Maude," no doubt to distinguish it from its sister product, ethyl alcohol.

Ethyl alcohol as an ingredient of numerous " drinks " has been consumed by man from time immemorial. As everyone knows, alcohol as an article of human consumption produces physiological and psychological reactions which are of great social significance. We cannot allow this aspect of alcohol to detain us here, but must pass on to its production and use for industrial and power purposes. We may at least pause to note, however, that whether the effect of ethyl alcohol on human beings is good or ill, there is no doubt whatever that all other alcohols are definitely poisonous substances even in relatively small quantities. Thus a distinguished chemist records that :

" Out of ten men who drink four ounces each of pure methyl alcohol in any form whatever, four will probably die ; two of them becoming blind before death ; the remaining six may recover, but of these two will probably be permanently blind. Even the absorption of its vapour through the lungs, or of the liquid through the skin, may produce permanent blindness." [1]

Coming now to the production of alcohol, the reader is probably aware that the processes of fermentation are brought about by the action of living organisms which secrete "enzymes"—that is, substances which promote chemical change. Much alcohol is at present produced by the action on certain sugars of a particular enyzme known as zymase, which is secreted by the micro-organisms called yeasts. Fermentable sugars may be obtained from various sources ; but the most important at the present time is starch, which forms the chief ingredient of maize, rice, wheat, barley, potatoes and other vegetable products. The processes involved in producing alcohol commercially may be illustrated by briefly outlining the sequence of events when potatoes are used as the raw material. The potatoes are first heated with steam under pressure in a closed vessel. After a suitable interval the pressure is suddenly released, the result being that the potatoes are converted into a mash. This contains starch in the form of paste. The starch is then converted into fermentable sugar through the action of an enzyme called diastase which is contained in malt. The product is known as maltose. After the liquid has been boiled off to destroy the diastase, yeast is added. The maltose is changed into glucose, which through the action of the zymase is converted into carbon dioxide and alcohol. There are also small amounts of other substances which for our present purpose may be ignored.

In addition to production with the aid of fermentation, alcohol can be made synthetically either from ethylene as extracted from coke-oven and ordinary coal-gas, or again from calcium carbide. Technical difficulties have still to be overcome, however, before synthetic alcohol can be made at a competitive price.

Though much of the alcohol manufactured at present is used for drinking, the spirit also has a very wide range of industrial uses, many of which are due to its remarkable properties as a solvent. To take a few industrial applications at random, alcohol is used for producing heat and light, and plays a part in the manufacture of varnishes, lacquers, stains, paints, enamels, felt hats, celluloid, xylonite, oilcloth, imitation leather, linoleum, soap, hair washes, photographic plates and papers, ether, chloroform, iodoform, acetic acid, dyes, explosives, surgical dressings, and fine chemicals. In addition it enters into numerous operations of which dyeing and cleaning in laundries and dye works may be mentioned as examples.

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[1] R. K. Duncan, in *The Chemistry of Commerce.*

Much research has been devoted in recent years to the possibilities of alcohol as a motor fuel. It is now well established that after necessary adjustments have been made, a petrol engine will operate successfully on alcohol ; though it is probable that thoroughly satisfactory running will not be secured without fairly drastic revision in details of design. In general, a motor actuated by alcohol is more difficult to start, it requires a higher compression, and is more liable to suffer from corrosion than when petrol is used. On the other hand, combustion is more complete, so that though the heat of combustion is lower than that of petrol, the thermal efficiency is much higher than might otherwise be expected. Alcohol has, moreover, very little tendency to detonate ; a fact which has been shown to contribute quite definitely to increased power and efficiency.

In the light of these facts there would appear to be good prospect of alcohol considerably amplifying our resources in motor fuel. Much will depend upon the possibility of securing ample raw material, without encroaching upon the world's food supply. No doubt also there will be numerous technical problems to solve before alcohol motors are as satisfactory and efficient as petrol engines. But development is likely to be hampered much more by excise restrictions than by technical difficulties. To prevent illicit drinking of alcohol intended for industrial use, governments insist upon such spirit being " denaturised "—in other words, rendered unfit for human consumption. This is done by adding methyl alcohol or some other substance equally repugnant to the taste. Methyl alcohol is commonly added in the form of wood naphtha, the resulting product being well known to all as methylated spirit.

The essentials of a really effective denaturant are that it should make the alcohol thoroughly unpleasant to drink, that it should not be possible to eliminate it by redistillation without trouble and expense, while at the same time it should not adversely affect the useful properties of the alcohol. Extraordinary difficulty has been experienced in finding such an ideal denaturant. Governments have in consequence been driven to frame restrictions which are a serious obstacle to fuller use of alcohol in industry. Denaturants have been a subject of investigation by chemists for nearly half a century; and it is to be hoped that before long some substance will be found which will make it possible to free alcohol to widen its sphere of usefulness indefinitely.

CHAPTER III

IRON AND STEEL

I

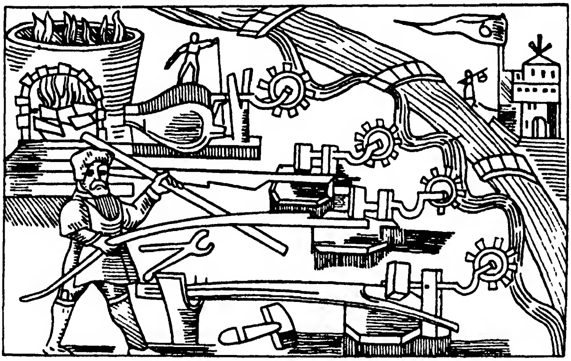
From Empiricism to Science

MAN's acquaintance with iron can be traced back through at least fifty centuries. But only in the past fifty years or so has he begun systematically to apply science to the manufacture of iron and steel. And in this latter period he has accomplished vastly more than in all the centuries which preceded it.

Most iron is found in Nature in the form of an oxide or carbonate known as iron ore, or ironstone. When this is subjected to heat the metal is separated, smelted or " reduced " from the ore. The better the ore the less heat is required, and so it frequently happened that the early workers produced quite good iron, despite lack of facilities, simply because they used good quality ore. The primitive methods of smelting iron persisted century after century with very little change. Agricola, writing in the 16th century, tells us that in his time good ore was smelted in a furnace consisting of an open hearth, in the centre of which a crucible was fitted. Into this crucible charcoal was first thrown, after which a layer of crushed iron ore, mixed with unslaked lime, was sprinkled over the charcoal. Alternate layers of ore and charcoal having thus been piled up into a heap the fire was kindled, and considerable heat generated by judicious use of the bellows, which were sometimes operated by water power. The ore having been melted, the slag was drawn off through a vent below the furnace, and a mass of iron was obtained which, after it had cooled, was hammered to remove pieces of slag adhering to it, and to condense and flatten the mass. It was thereupon placed on an anvil and beaten by a large water-operated hammer, and then, with the aid of cutters, was slit up into a number of pieces.

Finally, these pieces were reheated in the forge and shaped on the anvil by a smith into bars, or sometimes directly into articles such as ploughshares or iron tyres. The whole of these processes, as well as the methods adopted when lower-grade ores had to be smelted, will be found fully described and illustrated in Agricola's *De Re Metallica*, a translation of which into English has been made by Herbert Hoover and Lou Henry Hoover.

It was about the time of Agricola or a little earlier that cast iron first began to be made. Much larger and higher furnaces were constructed, capable of containing bigger quantities of ore and charcoal. In general the furnace developed into a truncated conical building, surmounting a bowl-shaped hearth of sandstone. The use of bellows in conjunction with such a furnace ensured the generation of heat sufficiently fierce to yield molten metal. This ran away through a vent at the bottom of the hearth, where it was allowed to gravitate into depressions prepared for it in a bed of sand. It was customary to make one large depression, called a sow, with a row of smaller depressions connected to it at right angles and known as pigs. The iron in the sow was subsequently broken up into pieces similar in size to the pigs. Hence the term " pig-iron." In this way the transition was made from the production of



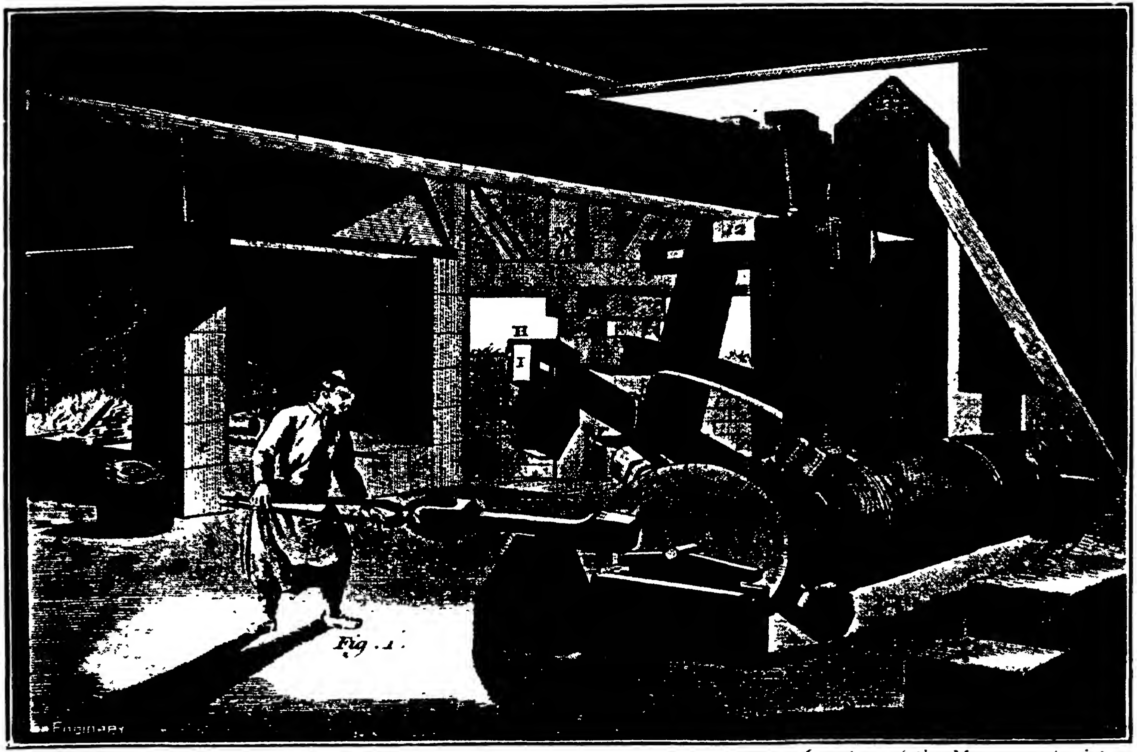
Water wheels operating bellows and tilt-hammers.
From Magnus, *History of the Northern Nations*, 1565.

wrought iron direct from the ore, to the manufacture of cast iron as a preliminary to wrought iron.

From the blast furnace the pig-iron was taken to the forge, when it was heated and hammered until a lump was obtained, called a " bloom." Further processes followed as before, involving the use of slitting wheels, cutters, and rollers, all worked by water, which converted the blooms into rods and flat bars of various sizes and shapes.

The production of cast iron was a tremendous step forward, completely altering the scale of iron-working for all time. It now became possible to produce really large masses of iron, cast in one piece, in the place of the smaller pieces laboriously hammered together, with which earlier workers had perforce to be contented. In this development we may find the first promise of the era of great castings, girders, bridges, cranes, steel buildings and other structures characteristic of the age in which we now live. To quote President Hoover on this matter, the change in method " marks the beginning of one of those subtle economic currents destined to have the widest bearing on civilisation."

We have so far said nothing about steel. Steel is a subtance which it is exceedingly difficult to define, a difficulty which increases from year to year. Generally speaking, commercial irons and steels vary according to the amount of carbon they have taken up in the process of heating, and also according to the amount of impurities they contain. So far as the carbon content is concerned, steel is intermediate between wrought and cast iron. The quality of the steel will depend upon the extent to which impurities such as silicon and phosphorus have been removed. To produce steel by such primitive means as those already indicated, everything possible must be done to ensure the requisite degree of carburisation, as, for example, by prolonging the period during which reduction of the metal takes place. The Hindus have produced a steel, known as *wootz*, from the earliest times by enclosing small pieces of wrought iron, together with some chopped wood or leaves, in unbaked clay crucibles, which are then placed in a furnace in which a high temperature is maintained. As might be



(Courtesy of the Newcomen Society.)

Iron-making in France with water-operated tilt-hammer.

expected, it is impossible to control such a process satisfactorily, and the composition of a metal made in this way varies considerably.

After the production of cast iron the next notable step forward was the introduction of pit coal for smelting purposes in 1620. So great was the consumption of wood in Britain prior to the use of coal that special Acts were passed and penalties imposed to prevent the countryside from being completely denuded of timber. Men thereupon endeavoured to find a satisfactory substitute for wood as fuel, and among these, Dud Dudley, the natural son of Edward, Lord Dudley, was the first to achieve success. Dudley, however, was before his time. He met with great opposition, and when he died the secret of his process died with him. About a century later the Darbys—father, son and grandson—were responsible for developing a coking process at Coalbrookdale. The great objection to coal for smelting purposes is that sulphur and other fumes are given off in the course of combustion. Coke resembles charcoal in that it is reasonably free from this defect. The industry now took on a new lease of life and a great increase in the production of cast-iron goods ensued. In 1779 the first cast-iron bridge was constructed and erected across the River Severn.[1]

While the Darbys were thus devising improved processes for iron manufacture, a watchmaker named Benjamin Huntsman was developing a process for making cast or crucible steel which has since been of the greatest importance to the industry. The exact date is not known, but he probably attained success between 1740 and 1770. Another momentous step at this period was the use in 1776 of one of Watt's engines for operating the blast at John Wilkinson's ironworks, as recorded in Book II. Steam was soon being used for other purposes about the ironworks as well, and as it became more widely adopted the production of iron and steel was increased and cheapened beyond all precedent.

In 1776 also the brothers Cranege invented the reverberatory furnace, in which conversion of pig-iron into malleable or wrought-bar iron, was carried out solely by the heat of the flame from coal, instead of iron and coal being mixed together as hitherto. In all such furnaces the flame in its course from fireplace to chimney is reflected or reverberated upon the matter beneath ; to which fact the furnace owes its name. The iron then being withdrawn from the furnace red-hot, was drawn into bars under the forge hammer. Peter Onions, of Merthyr Tydvil, carried the process a stage further in 1783. Having charged his furnace with pig-iron from the blast furnace, it was closed up and the crevices round the doors were luted with clay. A blast kept up the fire until the metal became less fluid and—in the words of the inventor—" thickened into a kind of froth, which the workman, by opening the door, must turn and stir with a bar or other iron instrument, and then close the aperture again, applying the blast and fire until there was a ferment in the metal." This was, in effect, what is known as a puddling furnace. Henry Cort, in 1783, combined and considerably developed the inventions of his predecessors, and now the introduction of the process of puddling is usually associated with his name. He also introduced the practice of reheating the iron after hammering and passing it through rollers to press out all the earthy particles and free the metal from dross, whilst simultaneously compressing it, as he himself expressed it, " into a fibrous and tough state." As a result of these and other developments, Cort was able to manufacture wrought iron on a scale hitherto undreamed of ; finishing it off, moreover, with a speed and accuracy also previously unknown.

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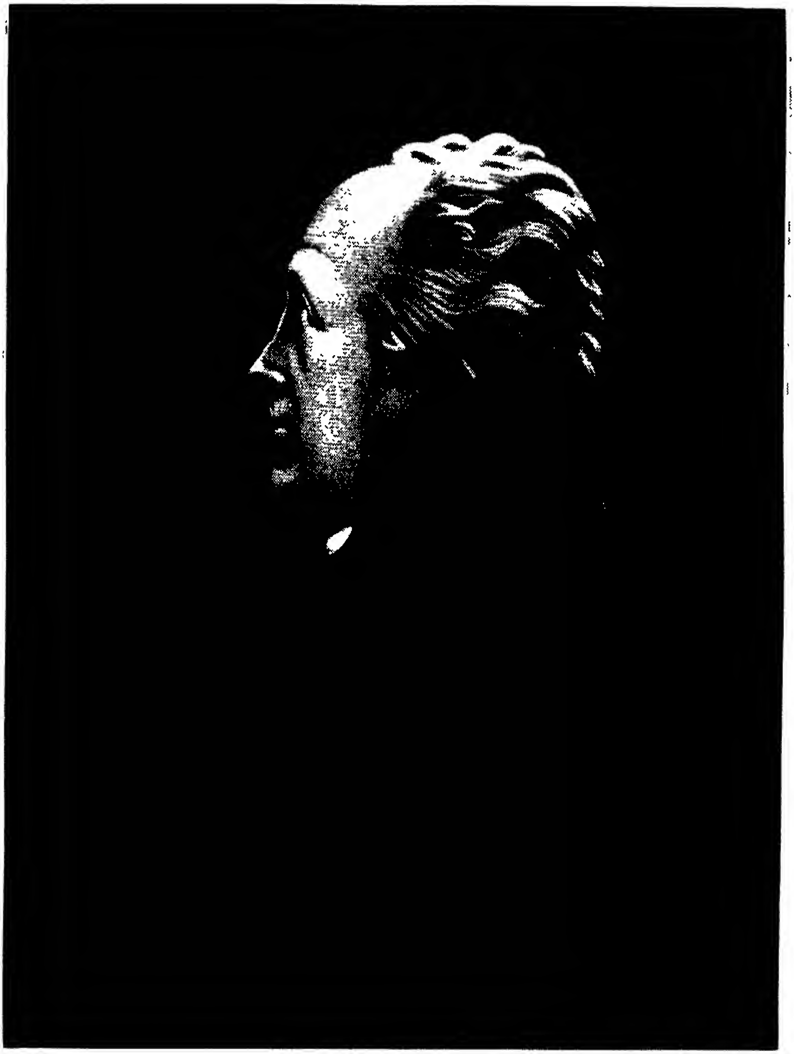
[1] The so-called "iron bridge" over the Orontes at Antioch (see Gibbon's *Decline and Fall*, Chapter LI) was not made of, but only partly plated with, iron.

In 1801 David Mushet discovered that the material called by miners " wild coal," and by them thrown away as useless, contained a large quantity of iron. This material is known as black-band ironstone. In 1828 James Beaumont Neilson, a gasworks manager, introduced the hot blast. This, together with Condie's water-cooled tuyere (the pipe through which the blast is carried), led to a further big increase in output. The consumption of coke was also reduced, while it now became possible to smelt ores previously unusable. Further improve-



(*Courtesy of " The Ironmonger."*)

Henry Cort, 1740–1800.

ments in puddling followed in 1835. Thereafter the Age of Steel dawned with the inventions of Bessemer from 1856 onward, and the development of the Siemens open-hearth process of manufacturing mild steel.

Bessemer's process was first made public in a paper which he read before the British Association at Cheltenham in 1856. From that time onward science has progressively replaced rule-of-thumb methods in the iron and steel industry. In 1864 came the use of the microscope for the examination of metals. The scientific testing of steel by chemical, mechanical, thermal, electrical, magnetic and other means, the heat treatment of steel, the use of the spectroscope, the production of alloys in which steel is combined with special elements such as chromium, nickel, cobalt, tungsten, vanadium, molybdenum, titanium, and uranium, the introduction of the electric furnace, the phenomenal increase in size of plant and truly staggering expansion of output—these and countless other developments testify to the vast benefits which accrue when an industry abandons empiricism for applied science.

2

Modern Methods in the Iron Industry

Iron in its pure metallic state is one of the rarest of metals. In combination with other elements it is one of the most abundant and widely distributed. And, using the term here to include steel, it is of all the materials man works upon the most indispensable to his progressive development as an engineer.

Practically all rocks contain iron, in quantities varying from a mere trace up to about 70 per cent. Rock containing less than 25 per cent. is not at present worth considering from a commercial point of view. Only a deposit which contains the metal in sufficient quantity for profitable extraction is known as iron ore ; while of the ore as it is mined the earthy, non-ferrous portion is called gangue.

Ores may be classified into groups, of which the most important are the oxides and carbonates of iron. Among the most valuable of the oxide ores is magnetite ($Fe_3 O_4$), which derives its name from the fact that it is magnetic. Its high value is owing to an almost complete absence of sulphur and phosphorus, the presence of which in the finished product robs it of its strength and tenacity. Another oxide of iron is hæmatite (Fe_2O_3), which is very widely distributed about the world and is found in a variety of forms.

The most important region in the world so far as the mining of iron ore is concerned is the Lake Superior region of America —particularly the State of Minnesota. The United States produce more iron than any other country, three-fifths of the ore being mined in Minnesota. Open pit mining is the usual method employed in the newer workings. The mine in this case is in effect a quarry. Dynamite is used to break down the material, much of which is quite soft, like red earth. Then steam or electric shovels scoop it up—from 2 tons a scoop and upwards—and drop it into the waiting trucks. In five minutes a 50-ton truck is filled ; and as fast as they are loaded the trucks are pulled out, made up into trainloads of fifty cars or more, and having been shunted over an automatic weighing scale the train is hauled away to the lake docks. The whole of these activities continue night and day without cessation. There are, of course, other methods of obtaining the ore, including underground mining, which is not always avoidable. Generally speaking, however, open-pit mining is adopted wherever possible. In the Mesabi range the ore has been found just under the roots of the grass.

In making iron the three ingredients required are ore, coke, and limestone. These are placed in a tall cylindrical structure, the blast furnace, which is filled from the top through an opening normally kept closed by a cone held against its seat by a counterpoise. The function of a blast furnace is to remove the oxygen and also the non-metallic impurities in the ore.

Before being taken to the blast furnace the lumps of ore are first submitted to a preliminary roasting in kilns. This expels the moisture and other volatile materials, while the carbonate is converted to oxide. Owing to the expulsion of the volatile matter, the ore becomes more porous and therefore more readily permeable by the gases of the blast furnace. The lumps are next broken to a moderate size, as, if too large, they are difficult to reduce. They must not be finely divided, on the other hand, as this would tend to clog the furnace and impede the passage of the hot gases through it.

Air for the blast furnace is preheated in stacks usually referred to as " stoves." These may be as much as 100 feet high and over 20 feet in diameter. Gas given off by the furnace itself is used for heating, being introduced with air into the combustion chambers of the stoves. Here the burning gas comes in contact with bricks arranged chequer fashion, the temperature of the brickwork being raised until it will absorb no more heat. The gas is then turned off. The air blast, which is supplied by blowing engines, is thereupon forced through the hot brickwork in the opposite direction, absorbing the heat ; after which it enters the furnace through water-cooled tuyeres. Here it passes through and burns the coke ; generating an intense heat in the lower part of the furnace. Carbon monoxide is formed, and the iron oxide is reduced to metallic iron with an evolution of carbon dioxide. The lime combines with silica and alumina from the ore and also with ash from the coke. The result is formation of slag, which floats on the molten iron and is drawn off from the furnace at frequent intervals. The metallic iron gravitates out and is run away either into pigs, or—as is more usual in large plants nowadays—into moulds fastened to an endless conveyor.

There have been various developments in the design of blast furnaces, but perhaps the most striking change is in the scale on which they are operated. So recently as 1880 the maximum production from a blast furnace was 1,200 tons a week. This was considered a remarkable advance on the older practice of 800 to 900 tons a week. Yet by 1910 output had been further increased to 600 tons a day. Now blast furnaces with an output of 1,000 tons a day are being built in the United States.

The ever-increasing scale of working has made mechanical handling appliances imperative. Hence the development of an entirely mechanically operated blast furnace. In the great works at Gary, controlled and operated by the United States

Steel Corporation, no human hand touches the ore from mine to furnace. Two thousand tons of raw material are delivered into each blast furnace by mechanical means every day. It is interesting to reflect upon the human drudgery which operation on this scale would have entailed in days gone by.

The large output furnaces of to-day are equipped with blowing plant capable of providing 60,000 cubic feet of air a minute against a pressure of 30 lbs. to the square inch. Careful control is as necessary in the case of this air as in regulating the supply of raw materials. The reader will remember that in Book II. we compared the supply of fuel to a steam boiler with the consumption of food by a living organism ; starvation resulting from too little food, indigestion following upon excess. This also applies to a blast furnace, very little variation from a satisfactory mean being sufficient to upset its digestive processes.

Enormous volumes of gas are generated by the modern blast furnace, and as considerable progress has been made in the efficiency of combustion of gas used for preheating the air, the surplus available for other purposes has been greatly increased. The modern blast furnace produces on an average 130,000 cubic feet of gas for every ton of iron made in it, or about one-third more than the volume of air supplied by the blowing engines.[1] Much of this gas can be utilised to advantage on the premises and sometimes in the immediate neighbourhood. A good example is provided by the steel works at Gary, Indiana. Here 30 per cent. of all the gas produced is used to heat the blast stoves. Some is consumed under boilers and some in giant gas engines which provide the blast, while some operates the unloaders at the dock. The gas is also used for steel-making processes, and helps to light the town of Gary. Contemplating these and similar developments it is well to reflect that within living memory most of the gas from blast furnaces (containing at least half the heat value obtainable from the fuel used) was entirely wasted. The idea of using

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[1] Another way of putting it is that, for every 1,000 tons of pig iron produced per week, the modern blast furnace will produce (in round figures) 1,000,000 cubic feet of gas per hour.

(*Courtesy of Messrs. United Steel Companies, Ltd.*)

An electrically charged blast furnace.

it to heat stoves and boilers was patented by Budd, of Ystalyfera, South Wales, in 1845, but the advance towards economy in this regard was at first very slow.[1]

We cannot even enumerate all the developments which in recent years have led or are now pointing the way to greater overall economy, but a few of the more important may be indicated. In 1904 James Gayley drew attention to the possibilities of lowering costs and increasing the regularity of working by drying the moisture out of the blast air. This was done by refrigeration, the moisture being precipitated in the form of snow. Again, cleaning the gas is a matter to which considerable attention has been given in recent years. Many difficulties and annoyances in operation can be traced to the fact that flue dust, in quantities from a few lbs. up to 800 lbs. per ton of iron made, is produced in the course of manufacture, and carried over with the gas to a large extent unless some means of checking it is provided. The gas may be cleaned by taking it through water, filtering it through textile fabrics, or again the dust may be electrically precipitated out of the gas by a highly ingenious system developed by Sir Oliver Lodge in Great Britain and Dr. Cottrell in America. Much remains to be done in this matter, there being many plants even now where no attempt is made to clean the gas. But quite as important as gas cleaning is the recovery of iron from the dust. Great quantities of this dust, containing as much iron as many of the ores used, are at present being wasted beyond recovery. When coal is the fuel used in the blast furnace the gas also carries over a certain amount of tar and ammonia, which can be recovered by suitable treatment.

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[1] The waste gases of blast furnaces were first used for roasting ores, and burning lime and bricks, between 1809 and 1811 by M. Aubertot, who in 1814 proposed the construction of furnaces for metallurgical purposes, specially designed to utilise such gases. M. Victor Sire, of Clerval, obtained a patent in 1836 for manufacturing wrought iron by means of blast furnace waste gas. Laurens and Thomas used waste gases in 1835–36 for steam raising, and in 1837 Wilhelm von Faber Dufaur succeeded in utilising the waste gases of blast furnaces in a reverberatory furnace and also for fining pig iron. Dufaur's success was widely commented upon; but it was not until Bunsen in 1838, and Bunsen and Playfair in 1845, made thoroughly scientific investigations upon "gases evolved from Iron Furnaces" that general interest was evinced in the possibilities of effecting economies by using blast furnace gas. The "bell and cone" device for closing the furnace at the top was introduced by George Parry in 1851, thereby facilitating the collection of the gases. B. H. Thwaite gave a great impetus to the use of blast furnace gas by demonstrating its suitability for generating power in an internal combustion engine in 1895.

Another important aspect of blast furnace economy is the utilisation of slag. Slag consists largely of a mixture of silicates of lime and alumina. So does Portland cement. It is not surprising therefore that practically unlimited use has been found for blast furnace slag in the manufacture of concrete. Tests on this material have proved beyond all question that it can be used for highway construction, reinforced concrete construction, pier and harbour construction—in fact, for any and all of the many uses to which Portland cement is now put. In this development we see one out of the countless links—often quite unsuspected by the general public—between activities which on the surface appear to be entirely independent of one another.

Reverting to the production of iron, we may note that while that which comes from the blast furnace contains over 1·5 per cent. of carbon, malleable or wrought iron contains not more than 0·25 per cent. Wrought iron is produced by a modification of Cort's puddling process. The quality of the product depends to a large extent upon the pig iron used as raw material. This should be as free as possible from phosphorus and sulphur, while the proportion of silicon should not be more than 2 per cent., nor less than 1 per cent. In the process of puddling oxidation of impurities takes place. Details of the processes adopted vary in different districts, but improvements on Cort's methods effected by Rogers in 1820 and Hall in 1830 have been generally incorporated in later designs of puddling furnaces.

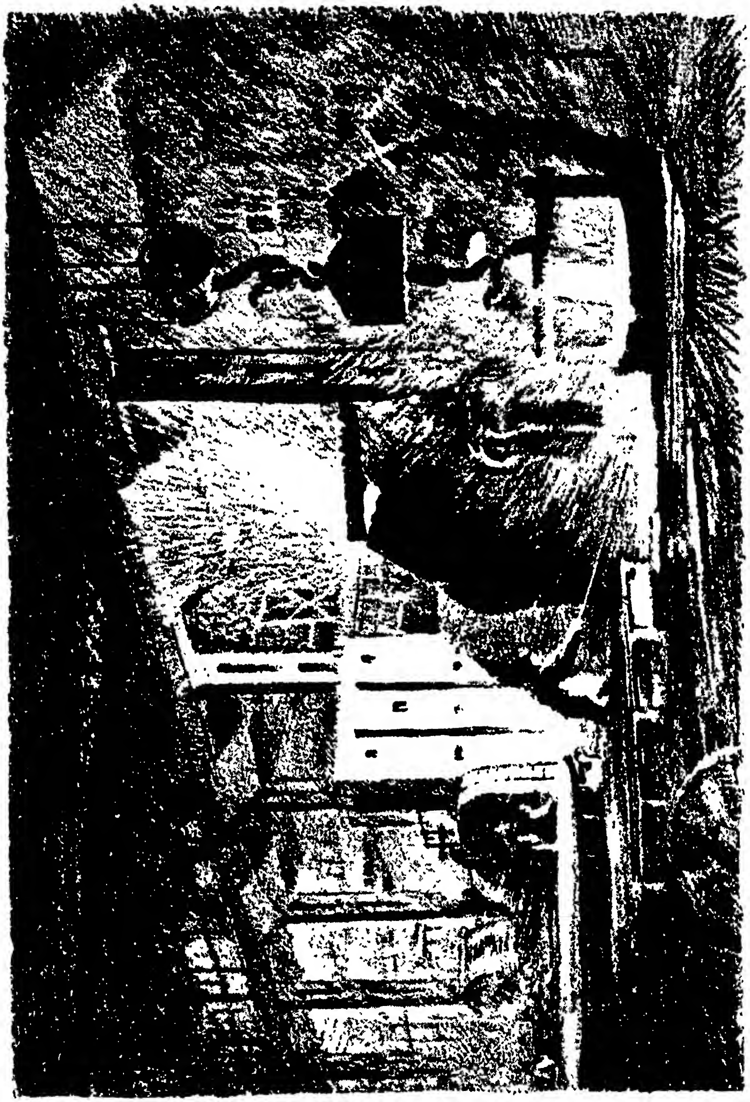
Good wrought iron possesses some very desirable qualities. It resists and recovers from sudden shocks and overstrain better than any other metal used for structural purposes. It also has the power of resisting corrosion to an unusual degree—a most important consideration for many kinds of work. Nevertheless, the coming of steel caused a rapid decline in wrought iron production. Steel could be manufactured cheaply on a large scale, while the production of puddling furnaces is limited to small quantities. The physical labour involved in puddling is, moreover, very heavy. Mechanically operated furnaces have been designed but cannot be regarded as altogether successful. So that, despite its undoubted virtues, the prospect of wrought iron being produced again in large quantities is now exceedingly remote. Steel to-day reigns supreme, and it is fairly safe to prophesy that it will for long continue to maintain its supremacy.

3

How Steel is Made

The story of steel is the story of man's endeavour to create a new metal. Nature having failed to anticipate the ever-increasing diversity of his industrial needs, the only alternative was to build up what he required synthetically. The metal he sought had to be durable, plentiful, cheap. It must combine strength with moderate weight. It must be ductile, rigid, flexible, elastic, plastic, hard or soft as required. And always it must be easy to transform, mould, and manipulate. What a quest ! Yet the story goes on to tell how in steel he so nearly found what he sought, that in a few years he has been enabled with it to reshape the whole material fabric of civilisation ; reaching pinnacles of achievement in construction which only a little while ago would have been beyond his wildest dreams.

Before discussing the methods adopted in its manufacture, it will be worth while considering once more the nature of steel. We have already commented on the difficulty of defining it. Sometimes we are told that steel is granular while iron is fibrous ; or again, that steel can be hardened while iron cannot. It has also been said that steel can be recognised by the amount of carbon it contains. Yet none of these statements is altogether satisfactory. The truth is that the characteristics of steel are so numerous and so variable that it is impossible to sum them up effectively in the brief space customarily allotted to definition. This we can say, however, that steel consists of iron, other than wrought iron, combined with not more than 1·5 per cent. carbon, together with small quantities of other elements. It may be said, further, that steel containing over



(*Courtesy of Messrs. Edgar Allen & Co., Ltd.*)

0·5 per cent. carbon will harden when heated and quenched ; though steel with a lower carbon content, known as mild steel, is not sensibly hardened by this procedure. This subject of

Sir Henry Bessemer in his 80th Year
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(*Courtesy of Messrs. Edgar Allen & Co., Ltd.*)

Sir Henry Bessemer, 1813–1898.

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heat treatment will be considered at some length in a later section. We may note here, however, that the important part played by carbon in determining the behaviour of steel when submitted to heat treatment has long been known ; having been first recorded by the Swedish chemist T. Olaf Bergson, who, in 1781, made an elaborate investigation into the differences in composition of cast iron, wrought iron, and steel. In 1822 Faraday established the fact that carbon exists in at least two different conditions in quenched and annealed steel respectively. Later, one of these was given the name hardening carbon, and the other cement or carbide carbon. Yet another, graphite carbon, is rarely, if ever, found in steel. It is quite commonly a constituent of cast iron, and tends to reduce the strength of that material.

Since wrought iron contains less carbon than steel, it will be apparent that any process for making steel out of wrought iron must involve the addition of carbon. Now if wrought iron is heated with carbon this element is taken up and steel is produced. The carburisation of wrought iron bar in this way was for long the only method of producing steel. In what is called the cementation process, bars of wrought iron, with charcoal packed round and between them, are placed in fire-clay boxes. These are sealed down with a layer of clay which is the " cement " from which the process takes its name. The iron is then brought to a bright red heat in furnaces of which the fire-clay boxes form a part. The steel so produced is called blister or shear steel ; " blister " because the bars when treated are found to be covered with blisters, and " shear " because this was the kind of steel used for making the shears formerly used for cropping woollen cloth.

The process of making cast steel by melting blister steel in fire-clay crucibles, first developed by Benjamin Huntsman, is still used in the manufacture of high quality tool steel. The invention marked a definite advance in the technique of the industry. But the first really momentous change in the method and scale of steel making was due to Henry Bessemer. In the process which he introduced, air is blown through molten pig iron contained in a vessel called a converter. The converter is first filled with molten iron and when air is blown through it the impurities in the iron are oxidised and eliminated. So also is the carbon, the metal left in the converter being practically pure iron. By adding measured quantities of ferro-manganese, or spiegeleisen, it is possible to recarburise the metal approximately to whatever extent is desired, while at the same time any excess of oxygen is removed.

Originally the converter was lined with an acid, siliceous material. It was found that phosphorus was not removed and so the process was limited to the conversion of pig iron having a low phosphorus content. Thomas and Gilchrist discovered at a later date that by using a basic lining of burnt dolomite (a double carbonate of calcium and magnesium) most of the phosphorus could be eliminated.[1] This is called the Basic Bessemer process, and was for a time much used in Great Britain. The phosphoric slag which is a by-product of this process makes an excellent manure. As good hæmatite, relatively free from phosphorus, is plentiful in America, the Acid Bessemer process is still widely adopted in that country.

The operation of a Bessemer converter is among the most spectacular events in steel making. As the molten material is poured into the converter a sunset glow lights up the scene with a weird splendour, while countless sparks shoot out in all directions. Then when the air is turned on it forces its way through the metal with a roar, while another great shower of sparks shoots upwards, changing colour as the carbon and silicon burn away. A flame also issues from the mouth of the converter, and, as the temperature rises owing to the formation and combustion of carbon monoxide, the contents boil up and the flame increases in size and brilliancy. Presently the sparks cease, the flame diminishes, the glow dies away. The operation is over. The spiegeleisen is added, and after again applying the blast for a short time the steel is poured into ingots.

Another method of making steel was developed on quite different lines by C. W. and F. Siemens.[2] These young German

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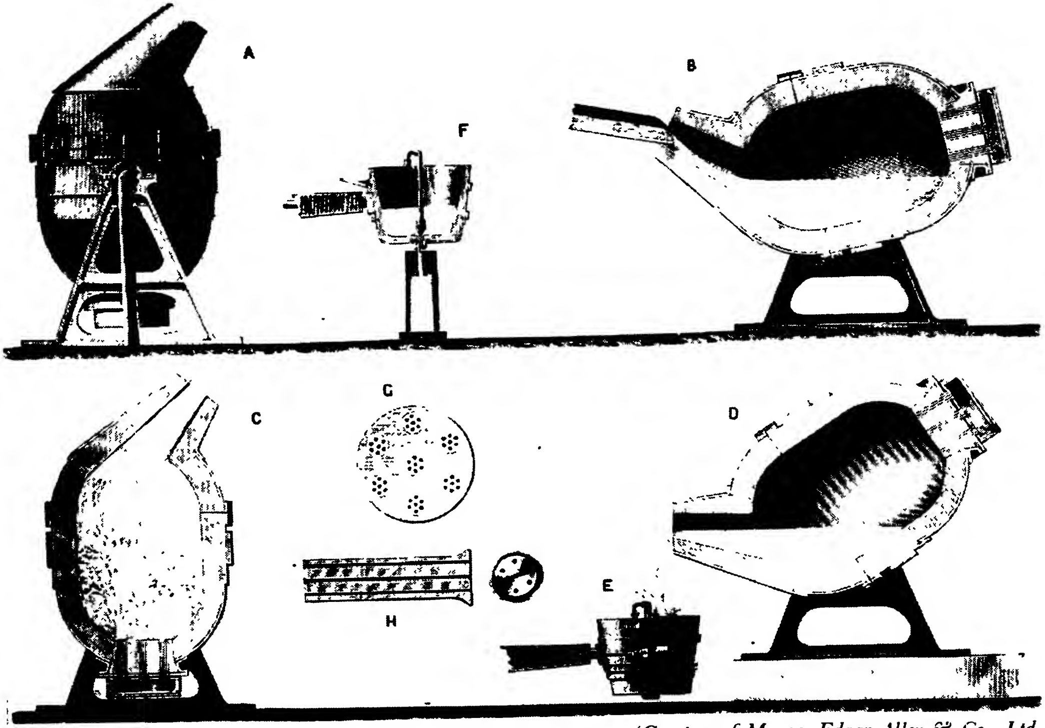
[1] The first patent was taken out in November, 1877, after many experiments had been made in the face of great difficulties.

[2] The success of the Siemens process was demonstrated in 1867—8.



(Courtesy of Messrs. Edgar Allen & Co., Ltd.

First form of Bessemer movable converter and ladle.

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(*Courtesy of Messrs. United Steel Companies, Ltd.*)

80-ton open hearth furnace in process of tapping.

[*To face p.* 29

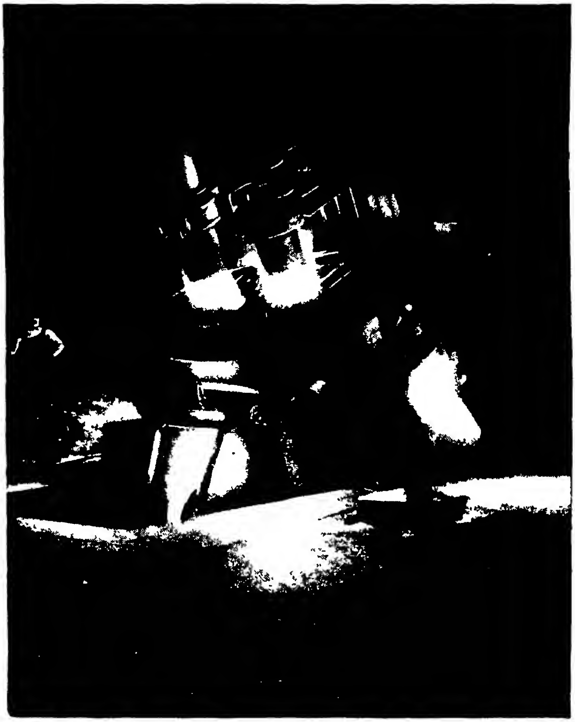
engineers began by experimenting in fuel economy, and succeeded in constructing a furnace in which the products of combustion were used to heat a chamber filled with brick chequer-work, the air supply to the furnace being then heated by bringing it in contact with the hot bricks. As we have already seen, this principle was also adopted for heating the air for blast furnaces. By using gaseous fuel and two sets of heat-saving chambers or " regenerators," both gas and air were raised to a high temperature before combustion and the thermal efficiency was materially increased. As applied to steel making the heat thus developed is passed over a hearth on which a charge of pig iron and hæmatite ore are placed. A further development was due to P. & E. Martin, who used scrap steel and pig iron only. In the original process the iron is exposed to the oxidising action of the flame, which together with the oxygen yielded up by the ore, removes the impurities. In both cases there must be additions of ferro-manganese to ensure the necessary recarburisation of the metal.

This method of making steel is also known as the open-hearth process. Although much more time is required to make an equivalent quantity of steel in this way than with the Bessemer converter, the open-hearth process is more amenable to accurate regulation, besides being more economical both in material and fuel. The possibility of utilising scrap is a notable step towards conservation of metal ; while not only is the economy in fuel striking, but continual progress is being made in this regard. During the past fifty years or so the consumption of the open-hearth furnace has fallen steadily from 1½ tons to 5–6 cwts. of coal to every ton of steel produced. It is not surprising therefore that open-hearth manufacture has gradually displaced the Bessemer process. Roughly speaking, the ratios of open-hearth to Bessemer output per annum are now ten to one in Great Britain and six to one in the United States. In Germany the disparity is not so striking, but there also the open-hearth process now leads in output.

Scientific control of the composition of the final product is manifestly of cardinal importance where the manufacture of so variable a material as steel is concerned. The introduction of electrical resistance thermometers has contributed materially in this regard by ensuring much more accurate regulation of furnace temperatures. But electrical science has given the steel maker still greater command of his product by providing him with the electric furnace.

There are several forms of electric furnaces used for steel-making purposes. The most important are the electric arc and the induction types. The former depend for the most part upon the heating effect of an electric current as it arcs across between two carbon electrodes, or between an electrode and the metal to be melted. In the induction type furnace the heat developed by a current induced in the metallic charge itself is utilised. The ease with which the temperature can be regulated, the very high temperatures which can be attained, and the complete absence of any possibility of contamination by products of combustion, are some of the advantages which make for uniformity and general high quality in the steel produced. Other points in favour of the electric furnace are that less labour is required and less space is occupied for a given output than in the case of other steel-making processes. The thermal efficiency, moreover, is remarkably high ; so that, despite the heavy losses unavoidably incurred in the conversion of heat into electricity and back again into heat, the electric furnace is still able to compete very effectively with furnaces of the combustion type in the production of tool and other special steels. Where energy can be generated sufficiently cheaply, the electric furnace can of course be used advantageously for the manufacture of ordinary grade steels as well.

Few people realise what a vast river of steel is now turned out annually by the various processes to which we have referred. Fifty years ago the total amount manufactured was approximately 4,000,000 tons a year. Now the world output is over 90,000,000 tons a year. In these figures we get a glimpse of the amazing progress made in the manufacture of this wonderful material, the evolution of which has possibly determined the trend of industrial and social development more than any other single discovery of modern times.



(*Courtesy of Messrs. Edgar Allen & Co., Ltd.*)

Pouring molten metal from an electric furnace.

4

Alloy Steels

Some of the earliest experiments with alloys of steel were made by Michael Faraday, an account of whose investigations appeared in the *Philosophical Transactions of the Royal Society* for 1822. He formed an alloy of steel and silver from which a number of excellent cutting tools were made, also a platinum steel alloy which was probably the first stainless steel ever produced. Of the latter product Faraday remarked that it was tougher (though less hard) than the silver steel, and that after months of exposure it was without a stain on its surface. Other alloys contained nickel and chromium.

As might be expected, having regard to the general lack of scientific data, Faraday's researches had little practical influence on the iron and steel industry. Other experiments were also made from time to time, but it was not until half a century later that a really useful alloy steel was produced, and then only by accident in the first place. About 1868 Robert Mushet discovered that a particular steel with which he was experimenting behaved in a peculiar manner. Everybody knows that tools made of ordinary carbon steel have to be first heated and then suddenly quenched to make them sufficiently hard to cut metals without rapidly losing their edge. Mushet found that this particular steel did not require to be quenched after forging. It hardened sufficiently if allowed to cool in the air, and tended to retain its hardness even when hot. Subsequent investigation indicated that this valuable property was largely due to the presence in the steel of the element tungsten.

Mushet developed his so-called " self-hardening " steel, of which several varieties were produced, but another quarter of a century elapsed before the new material came into general use. By that time steels were being made containing considerable amounts of tungsten, manganese, carbon, and silicon. Then the American engineers, Frederick W. Taylor and M. C. White—both of the Bethlehem Steel and Iron Works—began their exhaustive researches, eventually producing the first of the really rapid-cutting tool steels. This was an alloy containing large quantities of tungsten and chromium, with a high carbon content but low in silicon and manganese. The powers of resistance of this steel after special heat treatment were actually increased by a rise in temperature, with the result that tools made of it would work satisfactorily with their cutting edges red hot. The first public demonstration of the capabilities of the Taylor-White tool steel was made at the Paris Exhibition of 1900, causing a profound sensation throughout the engineering world.[1]

Prior to this development Sir Robert Hadfield, in 1882, discovered manganese steel, a discovery of the greatest significance, leading the way to the general development and use of special steels.[2] By systematic investigations with alloys containing progressively larger proportions of manganese, Sir Robert discovered that although about 2·5 per cent. of manganese produced a brittle alloy of no practical value, remarkable changes occurred when the amount of this element exceeded 6½–7 per cent. The strength and ductility increased, the metal in addition became non-magnetic, and there were various other changes, all indicating that a new type of material had been discovered.

It is not altogether surprising that one eminent metallurgist has described manganese steel as " one of the most marvellous materials ever brought before the public." This particular alloy is practically non-magnetic, notwithstanding that it contains about 86 per cent. of iron ; it is greatly toughened by quenching, instead of being hardened and made comparatively brittle as is the case with carbon steels ; and finally, its resistance to wear by abrasion is greater the more severe the conditions to which it is submitted. It should be clearly realised that these remarkable properties are only manifested when the

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[1] New alloys are now being produced for the manufacture of cutting tools that contain no steel at all. One of these, made by the General Electric Company of America, is composed of tungsten carbide and cobalt, and is known as carboloy. It is so hard that it can be used to machine glass rod.

[2] J. M. Heath took out a patent for the manufacture of a manganese steel on April 5th, 1839, and others produced manganese alloys ; but Sir Robert Hadfield was the first to discover the highly important properties indicated in the text. See *Metallurgy and its Influence on Modern Progress* (Chapman and Hall) for Sir Robert's own account of this matter.

(*Courtesy of Sir Robert A. Hadfield, Bart.*)

A railway junction constructed entirely of Hadfield manganese steel.

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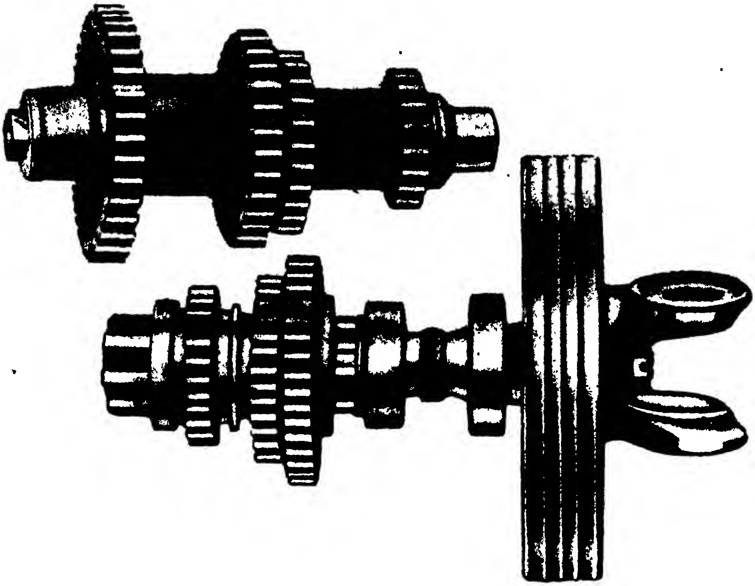
(Courtesy of Messrs. Edgar Allen & Co., Ltd.)

proportion of manganese is relatively high. Manganese is invariably present in all Bessemer and open-hearth steels, but usually not in quantities exceeding 1 per cent.

Manganese steel is so hard that it is very difficult to machine by ordinary means. This limits its general utility. It is, however, invaluable for special purposes, and is used extensively for tramway and railway switch points, rock-crushing machinery, the dippers of steam shovels, and other appliances subject to severe abrasive action.

Few men have contributed more effectively to the development of alloy steels than Henri Moissan. This distinguished French scientist, who began life in a chemist's shop and ultimately became professor of inorganic chemistry at the University of Paris, is now widely remembered for his researches into the possibilities of the electric furnace. This at his hands developed into a potent instrument for weakening the chemical and physical bonds which hold elements together. Every step which has enabled man to increase the range of temperatures at his command has also given him an increased range of materials with which to work. Realising this, Moissan took full advantage of the unprecedented temperatures attainable in the electric furnace, isolating for the first time many rare metals which, practically unheard of before his time, have since played so important a part in the production of alloy steels. This, indeed, was only one out of the many contributions to scientific advancement made by this brilliant *savant ;* it is, however, only this aspect of his work which concerns us here.

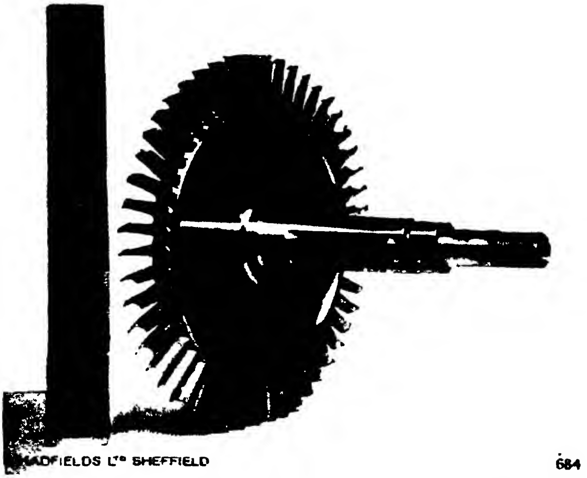
An army of other investigators has since added to our knowledge of rare metals, and their influence upon the properties of steel. Apart from tungsten and manganese, some of the more important metals used for making alloy steels are chromium, nickel, cobalt, vanadium, molybdenum, and silicon. The presence of chromium has a noticeable effect upon the temperatures at which critical changes in the atomic structure of the iron takes place, and gives to steel the property of air hardening in an even greater degree than tungsten. Hitherto chrome steel has been used largely for steel tyres and springs for railway rolling-stock; and, like manganese steel, for armour plate and armour-piercing projectiles. But perhaps the most widely interesting and useful characteristic of chromium is the fact discovered by H. Brearley that it imparts stain and rust-resisting properties to the steel of which it forms a constituent. Stainless steel contains from 11 to 15 per cent. chromium. It is one of the great labour and material saving discoveries of modern times, and doubtlessly led to the present rapidly extending use of chromium for plating purposes where it is desired to maintain an untarnished surface with a minimum of drudgery.



(Courtesy of Messrs. The Daimler Co., Ltd.)

Gear box lay-shaft and gears. The wheels are made from 5 per cent. nickel case-hardening steel.

An alloy of great interest to engineers is vanadium steel. Vanadium alloyed in small quantities gives quite remarkable results, a material being produced which combines high tensile


HADFIELDS Ltd SHEFFIELD
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(Courtesy of Messrs. Hadfields, Ltd.)

Rotor for exhaust gas turbine, made of special steel.

[*To face p.* 297

strength with resistance to vibration and sudden shock. It will be obvious that an enormous variety of uses can be found in modern industry for a material of this nature.

The extent to which alloy steels have already effected a revolution in practically all present-day activities is not always appreciated. It may be questioned whether there is a single industry or branch of commerce which has failed to benefit directly or indirectly by their use. Nickel and iron alloyed in suitable proportions can be used to increase the working capacity of a submarine cable to at least three times what it was previously. Acid-resisting incorrodible alloys have solved many difficult problems in the chemical industry. Engineering machine-shop practice has been raised to an altogether new level of achievement by the use of alloy tool steels. In the electrical manufacturing industry many uses for the new steels have been found, an excellent example being the adoption of silicon steel in the manufacture of electric transformers ; a procedure which has so increased the efficiency of this type of plant that power companies have been able to effect savings amounting in the aggregate to many hundred thousand pounds a year. Again, aluminium and magnesium steel alloys have become indispensable in the manufacture of both automobiles and aircraft. Turning to architecture, it is interesting to find that the original wrought-iron bars used by Sir Christopher Wren in St. Paul's Cathedral have recently been replaced by tie bars of non-corroding alloy steel. And as a final indication of the potentialities of the new alloys, we may draw attention to the exhaust gas turbine rotors constructed of Hadfield heat-resisting steel, many hundreds of which are now in use. These rotors are operated by the exhaust gases from aeroplane engines, running at speeds of 33,000 revolutions a minute at a working temperature of about 900° C. In view of the fact that inability to resist the action of even higher temperatures has hitherto been the main obstacle to the production of a practical gas turbine, may we not hope that before long this problem, too, will be solved by the use of alloy steels ?

5

Microstructure and Heat Treatment

When referring in the previous section to alloys of chromium and steel, we remarked that chromium affected the temperatures at which critical changes in the atomic structure of the iron takes place. This is a statement which requires some elucidation.

The structure and physical properties of steel can be profoundly modified by heat treatment subsequent to manufacture. To secure desired results various methods of heating and cooling steel were in course of time adopted, but for long this treatment was entirely empirical. The metal was heated and hammered, quenched and otherwise manipulated according to routines based on tradition and the judgment of more or less experienced craftsmen. Sometimes the desired qualities in the steel were secured, but as might be expected, results varied enormously. Anything in the nature of scientific control of processes and product under such circumstances was manifestly impossible. During the past half-century, however, an enormous fund of knowledge has been accumulated not only about the nature of the changes which occur during heat treatment, but also about the actual constitution of iron and steel with which these changes are intimately associated. And as modern ideas on heat treatment are difficult to grasp without some knowledge of theories which have been propounded and facts which have been established in recent years, we propose to discuss these matters briefly before turning to the actual methods adopted to modify the physical properties of steel.

The first step towards a more scientific procedure in the study and treatment of metals was made by H. C. Sorby, a geologist, who applied the microscope first to an examination of mineral structure and later to metallurgical research. Not being able to produce metallic sections thin enough to be transparent, he applied acid to the polished surfaces, bringing out the patterns which showed how the crystallised parts were held together. Sorby read a paper on the microscopic study of crystals before the Geological Society in 1857, and later published an account of the microscopic examination of metals. It must be confessed that Sorby's work had at that time very little effect upon those who were in charge of the iron and steel industry. Indeed, even so recently as 1890 this method of studying the structure of metals was still ridiculed by many British metallurgists, although in Germany considerable progress had been made in such work by A. Martens, E. Schott and others. But gradually prejudice was overcome and the microscope came into general use, until now metallography is universally regarded as being indispensable to the study of steel and its behaviour under heat treatment.

Another highly important product of science now equally indispensable is the thermo-electric pyrometer, originally devised by H. le Chatelier in 1891.[1] At that time Professor le Chatelier himself was very doubtful about the possibility of pyrometers being usefully employed in industrial workshops. And yet less than a quarter of a century later there were, at the works of the Hadfield Company alone, some sixty assistants devoting practically the whole of their time to making over 50,000 readings of high temperatures by means of electrical and optical pyrometers every week ! While the microscope reveals a multitude of modifications in the appearance of steel quite invisible to the naked eye, the pyrometer enables the changes in temperature responsible for these alterations to be observed and recorded with very great facility and precision. Thus, watching and measuring, the metallurgist can now learn infinitely more about the constitution and behaviour of steel, and exercise far greater control over its manufacture and manipulation, than when reliance was placed entirely upon empirical rules and the unguided experience of " practical " men.

Now certain peculiarities in the behaviour of steel when being heated or cooled have long been noted. If a piece of steel is allowed to cool from, let us say, 1,000° C., and its temperature is accurately measured at regular intervals, it will be found that cooling continues down to a certain point, whereupon the process is suddenly retarded, and the temperature may even rise for a time. Then cooling is resumed, to be retarded again presently and again resumed. Finally, the steel cools without further interruption until the temperature of the atmosphere is reached. Similarly, during the heating of the metal, points are reached at which there is an absorption of heat, causing a temporary retardation in rise of temperature.

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[1] Josiah Wedgwood made the first recorded attempts to determine high temperatures accurately, about 1782. See Hadfield's *Metallurgy and its Influence on Modern Progress.*

The points at which the process of heating or cooling is retarded are called critical points. And since during the retardation of cooling sufficient heat may be evolved to produce a visible glow, this retardation is referred to as recalescence.[1] It has been found that in low carbon steels there are at least three such critical points, which vary according to the percentage of carbon present in the steel. The second point reached in the process of heating up is now known to be almost identical with the disappearance of magnetism in iron, while the third is characterised by a sudden change in the law of variations of electric resistance. From these and other facts the deduction has been made that iron, like carbon, exists in different allotropic forms under different conditions of heat, mechanical treatment, and degree of purity. In other words, a change of internal energy is believed to occur in the metal at the critical temperature without necessarily being accompanied by a change of state. Professor H. M. Howe has further suggested that this phenomenon is due to a change in the arrangement of the atoms, a view which more recently has been materially reinforced by the use of X-rays in the exploration of crystal structure. This method of research takes us far beyond the range of the most powerful microscope, revealing indeed the arrangement of the very atoms of which materials are built up. Sir William Bragg, who has carried out much of the pioneer investigation of crystal structure by means of X-rays, records that at the critical points in the heating and

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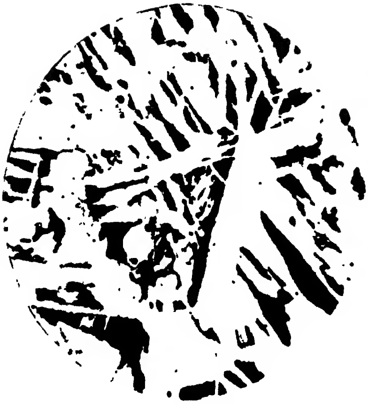
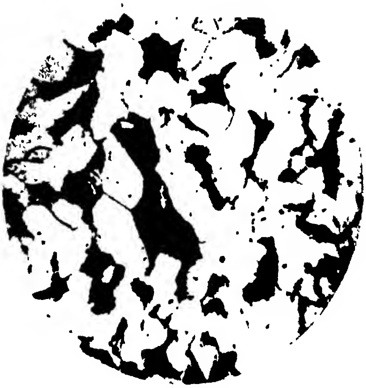
[1] The phenomenon of recalescence was discovered by the late Sir William Barrett, F.R.S., who reported his discovery at a meeting of the British Association, 1873, and recorded it in a paper published in the *Philosophical Magazine* in the same year.

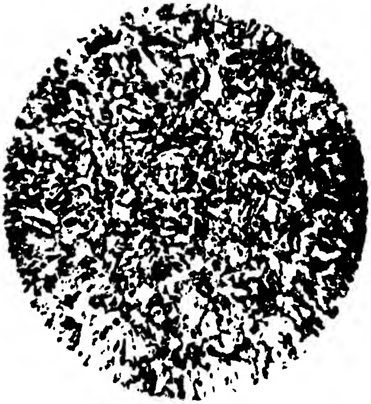


Structure as cast.



Annealed at 920° C.

Normalised at 920° C.



Quenched in water at 920° C., re-heated to 600° C. and cooled in air.

Micro-photographs showing effect of heat-treatment on a pure iron carbon mild steel (*Messrs. Edgar Allen & Co., Ltd.*).

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cooling of iron and steel the atoms do actually rearrange themselves into different groupings.

It is customary to indicate these critical points by letters and numerals. Thus A_1 indicates the lowest critical temperature, A_2 the intermediate, and A_3 the highest point. But since the critical points occur at rather lower temperatures on cooling than on heating, the cooling points are distinguished by the symbols Ar_1, Ar_2 and Ar_3, and the heating points by Ac_1, Ac_2, and Ac_3.

The A_1 change is associated with modifications in the carbon in the steel. Carbon which was in solution in the iron at higher temperatures is at this point precipitated as carbide of iron in thin layers alternating with layers of iron. This carbide of iron is called cementite, and it is this formation which gives to steel its peculiar strength and toughness. It is one of four micro structures now universally recognised as being of primary importance in the constitution of steel. The others are ferrite, pearlite and martensite. Briefly, ferrite consists of crystals of practically pure iron, and is the chief constituent of soft steel which has been slowly cooled below the critical point Ar_2. Pearlite is an intimate mixture of ferrite and cementite. It takes its name from its pearly appearance under the microscope. Martensite is the name given to the formation characteristic of steel when quenched suddenly from high temperatures.

Hardened carbon steel contains its carbon in solution in the iron, so that when hardening it must be heated above the critical point Ac_1. At this point the carbon—which X-ray investigation tells us is held in solution in the space between atoms in the crystals—is dissolved ; and to retain it in solution rapid cooling must be resorted to so that there is no time for the carbon to come out of solution again during the cooling process. The degree of hardening which can be attained by quenching depends largely upon the percentage of carbon in the steel. Steel hard enough to mark glass must contain at least 0·5 per cent. carbon.

There are several other heat treatment processes besides hardening. " Normalising " means heating a steel to a temperature beyond its upper critical point and allowing it to cool freely in air. The object is to produce a fine grained metal. " Annealing " involves reheating, followed by slow cooling. This softens the metal, reducing internal strains set up by previous operations. " Cementing " implies heating a steel above its normalising temperature in a medium which will increase its carbon content. One form of cementation is known as " case hardening," the surface only of the steel being impregnated with additional carbon, so that the outside may be hardened by quenching, while the interior remains soft and tough. " Tempering " means heating a steel to definite temperatures below the A_1 point in order to obtain definite degrees of hardness.

It should be stated that there is still enormous scope for research so far as the nature and behaviour of steel is concerned. Despite rapid progress in recent years, much remains obscure. One very promising field for further investigation is the effect of heat upon the orientation of crystals in iron and steel ; properties such as elasticity and tensile strength being apparently dependent (at least in part) upon random orientation ; regular orientation resulting in weakness in particular planes.

But though much remains to be done, the progress already made in iron and steel manufacture since the adoption of scientific methods can only be characterised as astounding. Surveying the industry as it is to-day, and bearing in mind the rapidity with which scientific control of its processes is being achieved, it is difficult to realise that only a few decades ago the attitude of most of those engaged in steel making was one of hostility to experiment and " theorising." To one youth who wished to receive a training in science before entering the works, his father replied : " Go to a technica college ? Not if I know it, my boy. You will learn your job where I did—in the School of Hard Knocks ! " But to-da the voices of those who hold such views are seldom heard They have been silenced by the unanswerable and overwhelming logic of tangible results in industry.

6

Moulding the Product

The processes by which iron and steel are moulded to the shapes required for industrial purposes vary greatly. Processes which involve the use of machine tools have already been indicated in Book II. Here we shall glance round the foundry, the forge, and the rolling mill.

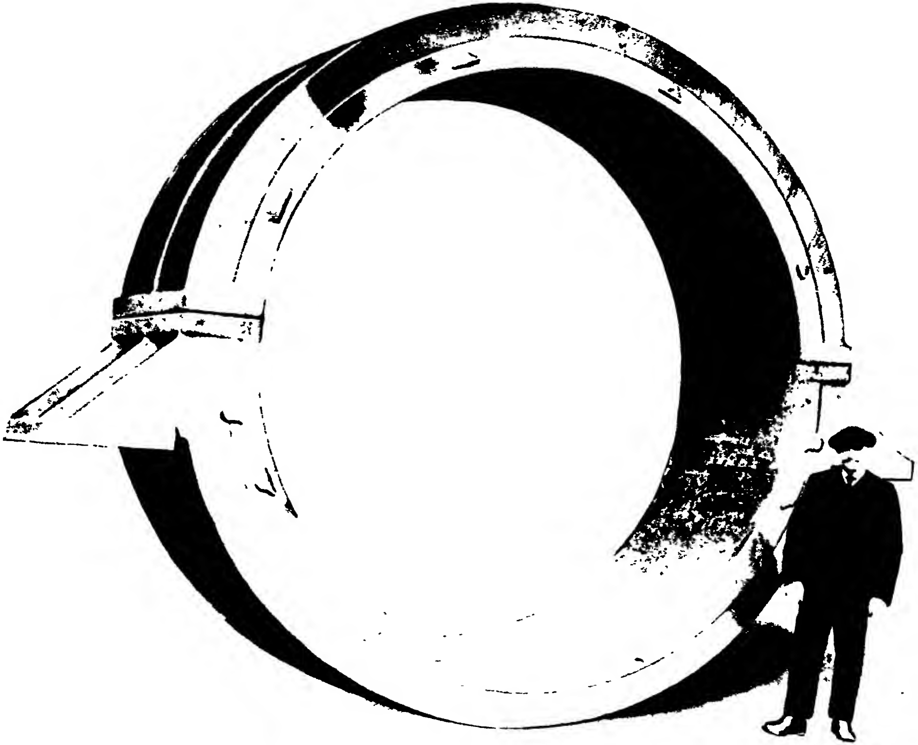
Foundry practice involves pouring molten metal into moulds and allowing it to set and so take the shape of the mould. The metal for pouring is melted in a small blast furnace called a cupola. In general, a mould is formed in sand. A pattern is first made of wood, similar in shape to the article which is to be cast, but allowing for the shrinkage which takes place in the metal as it cools. The pattern is then bedded in the sand. The sand used must be very refractory, just plastic enough to retain the form of the impression made by the pattern. Moulding may be effected in the sand directly the pattern is removed, in which case it is called " green-sand " moulding, or the mould may be dried in a stove and coated with black-lead before use. Usually the mould is made in two parts, which are fixed together before pouring the metal. Passages for the entry of the metal are made through the sand in the top part of the mould, and vent holes are also provided for the escape of gases formed, and air displaced. For large work a pattern may be dispensed with, a mould being carefully built up with bricks and loam made of sand and clay. When a hollow space is to be provided in the article about to be cast, a body made of sand and known as a " core " is built up separately and placed in the mould after the latter has been prepared. Casting by means of moulds and cores has been practised from before the dawn of history, as indeed we have already seen in Book I, Chapter II, Sec. 6.

In recent years considerable progress has been made in the development of mechanical appliances for making moulds. Generally speaking, moulding machines are designed to cope with work of a repetition character. In addition to greater speed of production, the castings obtained from moulds made by machinery are cleaner, more accurate, and have a smoother surface than can be secured with hand-made moulds.

A very interesting modern development is the manufacture of cylindrical castings by what is known as the centrifugal process. Pipes and similar products, when cast in moulds, are apt to be thicker on one side than the other owing to the difficulty of ensuring that the core is placed concentrically. In the centrifugal method of casting, as developed by F. W. Stokes and others, a solid mould is rapidly rotated and molten metal poured into it. The metal is held against the inside of the mould by centrifugal force, forming an annular ring or pipe of molten metal which gradually cools and sets. Pipes produced in this way are not only of even thickness throughout, but the iron also is of a closer grain, and freer from holes due to air bubbles, than when ordinary methods of moulding are adopted.

Air bubbles, forming cavities known as " blowholes," give considerable trouble in the steel foundry. Molten steel gives off quantities of gas which may be many times the volume of the steel itself. As the metal cools the liberation of gas causes a gentle bubbling, or on occasion may even produce the appearance of violent ebullition. It is, of course, not the gas which is liberated, but that retained in the metal as it sets which is the cause of blowholes. Both physical and chemical methods are adopted to ensure maximum liberation of gas. Mechanical agitation of the liquid facilitates this process, and evolution of gas can be hindered, if not arrested, by casting under pressure. Chemical methods involve the addition of substances such as silicon and aluminium. The action which takes place is not yet fully understood, but there can be no doubt about the process being effective. It is believed that the solvent power of the steel is increased, so that the gases are retained in solution as the metal cools and sets. The ebullition of the molten metal quickly subsides, while the castings produced are free, or practically free, from blowholes.

Steel castings are now submitted to an elaborate heat treatment. For this purpose a furnace ensuring an even temperature throughout is necessary, and the temperature



(Courtesy of Messrs. Edgar Allen & Co., Ltd.)

Dynamo magnet steel castings 16 feet diameter.

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must be under complete and continuous control, preferably by the use of a recording pyrometer which registers all variations. The heat treatment may take the form of annealing, normalising, or quenching, followed by tempering.

As a result of these and other modern developments huge castings of intricate design are now produced with an accuracy, and a soundness and quality of material, which leave little to be desired.

Although engineers generally refer to foundry practice when using the word " moulding," it is, of course, equally applicable to other processes by which iron and steel are shaped as required. Turning now to the forge and the mill, we have to note that the iron obtained from the puddling furnace must first be subjected to much hammering and squeezing, to eliminate the slag still contained in the interstices of the metal which is at this stage soft and only loosely coherent. The metal is therefore taken while still plastic and hammered under steam hammers. Sometimes squeezers, either of the jaw or roll type, are used. Under the hammer showers of red-hot liquid slag are expelled, after which the " bloom " of iron is passed immediately to the rolls whilst still red-hot and rolled out into bars and other sections.

The function of the rolls is to reduce the thickness of metal to form a plate, or to reduce both thickness and width, thereby increasing length and producing a bar. This, of course, is simply doing on a large scale what a smith does by hand when drawing out a piece of metal between hammer and anvil. Two or more pairs of rolls are used, the metal passing first through the roughing rolls to those which reduce it to its final form.

The processes for steel are much the same as those for iron, the main difference being that the machinery required for dealing with heavy steel ingots must necessarily be much heavier and stronger. Any one of several arrangements of rolls may be adopted according to circumstances. The mills are referred to as " two-high " or " three-high," depending upon the number of rolls used. Mills for light work are often worked continuously in one direction, the metal passing through the rolls and then being returned over the top. In three-high mills, also worked continuously forward, the metal passes in one direction between the bottom and middle rolls, and is then returned between the middle and upper rolls. Work is therefore done on the steel in both directions, idle time and transport being to that extent avoided. Reversing rolls have their direction of rotation reversed at each pass, the metal being rolled in both directions between the same pair of rolls. The largest and strongest mills are called " cogging " mills. These reduce heavy ingots to a bar or other section suitable for further treatment between the smaller rolls.

The steady increase in the scale of rolling mill plant and operations during the past fifty years is directly traceable to the general substitution of steel for wrought iron in industry. Steel, as we have seen, can only be produced economically in large quantities. Steel ingots have so increased in size and weight that mechanical handling equipment is now absolutely essential. Tables for lifting, " manipulators," live rollers for longitudinal, and skids for lateral transfer of material, are some of the accessories without which output on a modern scale would be quite impossible. The quantities dealt with and size of individual sections and plates rolled have increased in proportion. Since the advent of steel, for example, the output of rails has increased from about 600 tons a week to over 10,000 tons a week in some of the largest American mills. Ship-plates have increased from 8 feet in length for the first iron plates to 36 feet, which is the usual length for steel plates at the present day. In about the same period the manufacture of " tinplate "—that is, steel plate coated with tin—has in South Wales increased from about 50,000 tons to 600,000 tons a year, while in America it has jumped from nothing to approximately 2,000,000 tons a year. It is worth recording that the Welsh tinplate industry now consumes more steel than any other single industry in Great Britain, the annual production being sufficient to surface a road 30 feet wide and over 27,000 miles long.

CHAPTER IV

OTHER METALS

I

Copper : Its Production and Refinement

THE reader will recollect that we discussed the discovery of metals and the beginnings of smelting and founding in Book I. It was there stated that archæological research has not thrown much light on prehistoric methods of smelting metals, and we may now add that even when we come down to the time of early written records little information is to be gleaned. Pliny, for example, like other early writers, is vague in his references, and uses one word indifferently to designate copper, bronze, and brass. No clear description of the processes employed (which no doubt remained much the same for several thousand years) is known to date back earlier than the 12th century A.D., when the monk Theophilus recorded very lucidly the methods of copper smelting and refining practised in his time. The following particulars, quoted in a footnote to Hoover's translation of *De Re Metallica*, are reproduced here as being of considerable historical interest, and at the same time forming a striking contrast with modern methods to be described presently :—

> " Copper is engendered in the earth. When a vein of which is found, it is acquired with the greatest labour by digging and breaking. It is a stone of a green colour and most hard, and naturally mixed with lead. This stone, dug up in abundance, is placed upon a pile and burned after the manner of chalk, nor does it change colour, but yet loses its hardness, so that it can be broken up. Then, being bruised small, it is placed in the furnace ; coals and the bellows being applied, it is incessantly forged day and night. This should be done carefully and with caution ; that is, at first coals are placed in, then small pieces of stone are distributed over them, and again coals, and then stone anew, and it is thus

arranged until it is sufficient for the size of the furnace. And when the stone has commenced to liquefy, the lead flows out through some small cavities, and the copper remains within. . . . Of the purification of copper. Take an iron dish of the size you wish, and line it inside and out with clay strongly beaten and mixed, and it is carefully dried. Then place it before a forge upon the coals, so that when the bellows act upon it the wind may issue partly within and partly above it, and not below it. And very small coals being placed round it, place copper in it equally, and add over it a heap of coals. When, by blowing a long time, this has become melted, uncover it and cast immediately fine ashes of coals over it, and stir it with a thin and dry piece of wood as if mixing it, and you will directly see the burnt lead adhere to these ashes like a glue. Which being cast out again superpose coals, and blowing for a long time, as at first, again uncover it, and then do as you did before. You do this until at length, by cooking it, you can withdraw the lead entirely. Then pour it over the mould which you have prepared for this, and you will thus prove it to be pure. Hold it with pincers, glowing as it is, before it has become cold, and strike it with a large hammer strongly over the anvil, and if it be broken or split you must liquefy it anew as before."[1]

Even fuller details of the various processes were given by Agricola several hundred years later. His methods appear to have been much the same ; and even when we come down to an account of copper smelting written in 1835 we find that the methods in vogue at that date, except for the use of coal and an increase in scale of working, were such that Agricola might have followed them with interest and complete understanding.

The fact is that more progress has been made in copper mining, smelting, and refining in the past thirty years than was made in thirty centuries previously. Among the many revolutionary developments which have taken place since the beginning of the present century may be mentioned the introduction of " froth flotation " for separating the mineral from the gangue or worthless material ; the great economies effected by new methods of mining, and particularly by the use of steam and electric shovels ; reduction of cost due to using pulverised coal for reverberatory smelting furnaces ; and the great increase in scale of all operations. The nature and significance of these developments will be made clearer as we proceed to give an outline of present-day methods of producing and refining copper.

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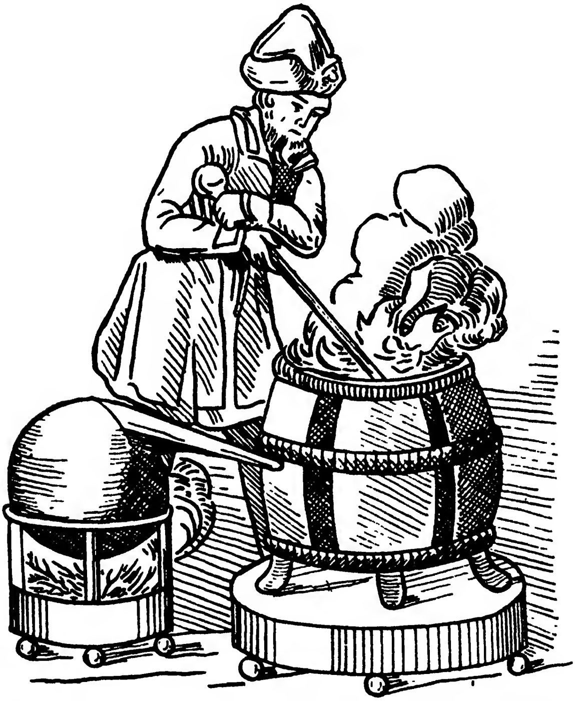
[1] From a translation by Robert Hendrie, London, 1847.

Many compounds of copper as well as metallic copper occur in nature. The smelter classifies ores according to the treatment necessary for the extraction of the metal; the usual classification being native copper, oxide ores, and sulphide ores. Here we shall confine our attention to the last group, from which the bulk of the world's supply of copper is derived.



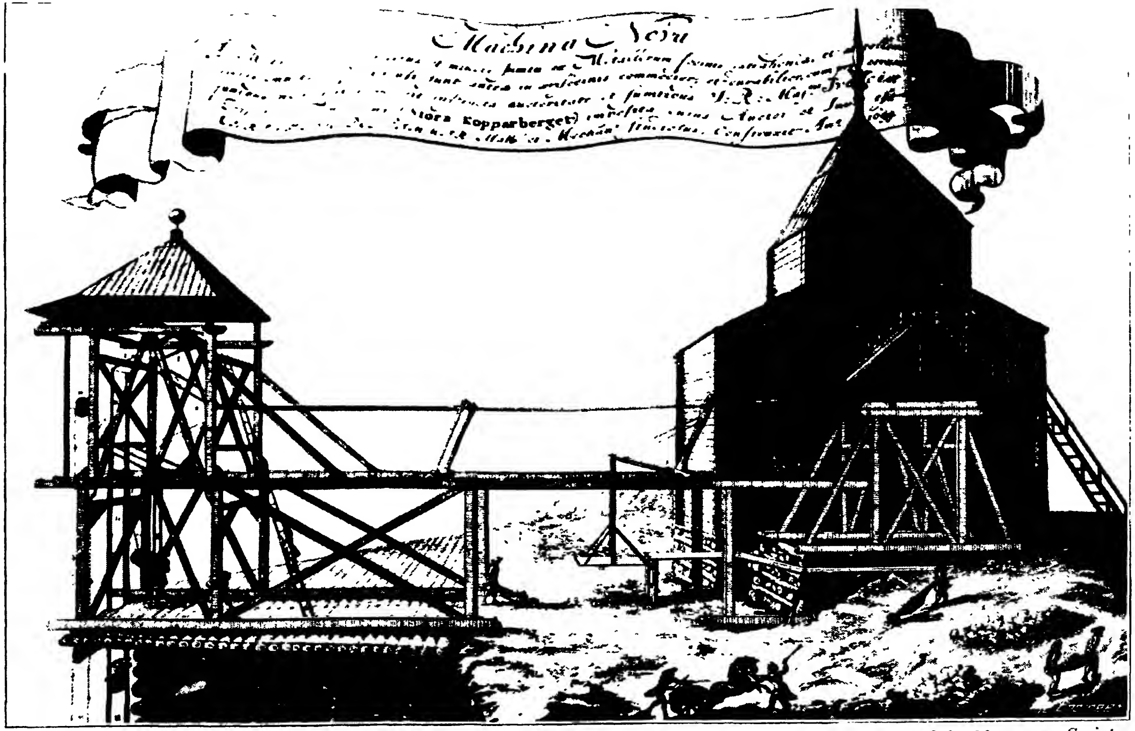
Smelting copper ore with the blast of an eolipile.
(From *Aula Subterranea*, 5th ed., 1736.)

Before mining operations begin, either the overburden—the material lying above the ore—is stripped off, or, when the ore lies at too great a depth for stripping, mining by caving is adopted. When using steam shovels the overburden is removed and then the ore is blasted down by dynamite in quantities of many thousands of tons. Specially large boulders are then further disintegrated by blasting, though modern steam and electric shovels can handle surprisingly large pieces with ease. Thus one of the latest types of electric shovel is capable of shifting in one scoopful enough earth to fill a trench 1 foot deep, 6 feet wide and 68 feet long ; or, alternatively, to fill eight large motor trucks. This load of material can be lifted to a height of 100 feet and deposited anywhere within a radius of 100 feet from the centre of operations. The whole contrivance is controlled by one man by means of two hand levers and one set of foot pedals. It would be interesting to know what Agricola would think if he could be suddenly confronted by this feature of modern mining !

The alternative process, caving, involves opening permanent roads or galleries under the mass of ore. Passages up to the ore are then made, and branch galleries of smaller dimensions are driven into it. The ore is so undercut in the process that its support by rock pillars is reduced as far as safety will permit. These pillars are then blasted out and the ore falls down, sufficiently disintegrated for removal to the main galleries, whence it is taken away in cars.

The refuse in the material as it is mined is generally far in excess of the valuable portion, and should normally be got rid of as speedily as possible, so as to reduce cost of handling and transport. This is known as concentration, a process which may be unnecessary where very high-grade ores are concerned, and even inadvisable when the gangue contains materials which would assist the smelting process.

The preliminary stage of concentration usually involves crushing the ore and swilling away the refuse with water, the material being passed over a screen which is oscillated rapidly to and fro. There are several alternative and supplementary processes, but these need not detain us here. The point which it is important to emphasise is that by introducing a further stage of concentration called froth flotation, much valuable mineral which previously would have been lost is now saved ; while ores which formerly were considered too low-grade to be


Machina Nova
Stora Kopparberget

(*Courtesy of the Newcomen Society.*

Water-operated headgear for haulage at the Stora Kopparberget, the famous copper mine in Sweden. From Nauclerus, 1702.

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worked are now treated for the extraction of copper. Briefly, froth flotation depends on the differential power with which water adheres to different bodies. When crushed sulphide ore, suspended in water, is mixed with a small quantity of oil and then subjected to violent agitation, the copper minerals rise to the surface in the form of a froth, while the gangue settles down at the bottom. It may serve to illustrate the beneficial effects of this process to note that it has increased the extraction of valuable material by at least 20 per cent. Froth flotation has also proved of great value in a number of other industries.

After concentration the ore may be roasted to remove a portion of the sulphur, and is then taken either to a blast furnace or a reverberatory furnace for smelting. The products so obtained are copper " matte " and slag ; matte being a mixture of copper and iron sulphide. This material is submitted to an operation similar to the Bessemer steel-making process, air being blown through it while in a molten state in a converter, expelling the iron and sulphur. The crude copper left in the converter must then go through the final stages of purification and refining.

Purification in a furnace does not completely eliminate all impurities. Small amounts of gold and silver and base metals are still left in the copper. The gold and silver must be recovered for sale, while all other impurities must also be removed if the copper is required for electrical purposes, the presence of impurities seriously impairing the electrical conductivity of the copper. A process of electrolytic refining is therefore adopted, the copper being dissolved by electrolysis and redeposited in pure form ; the gold, silver and other impurities falling to the bottom of the electrolysing tank.

Rapid progress with industrial electrification has greatly increased the demand for copper. Modern methods of production, however, have enabled supply to keep pace with demand. The output of the industry fluctuates considerably, much depending upon the market prices which for this commodity are singularly unstable, tending to follow the ebb and flow of trade very closely. In recent years, annual world production has been between one million and one-and-a-half million metric tons a year.

2

Aluminium and what it has made Possible

And now we come to a metal which, compared with copper, might almost be said to have no history. Its existence was entirely unsuspected until the 18th century, it was not isolated until the 19th, and did not come into general use until the century in which we now live. Stahl, who did so much to develop the theory of phlogiston, appears to have been the first to suspect that it was an individual substance. Sir Humphry Davy was convinced that it was a metal, and in anticipation of its discovery called it alumium ; a name which he later changed to aluminum,—this having in course of time become aluminium.[1] The actual discovery was made in 1827 by Wöhler, who heated aluminium chloride with pure potassium and succeeded in obtaining aluminium in its metallic state for the first time in history.

H. St. Claire Deville took matters a stage further by concentrating upon the production of aluminium on a commercial scale, and in 1855 the first factory for this purpose was established at Javel. Deville tried both electrolysis (decomposition by the agency of electricity) and the reduction of aluminium chloride by chemical means, and succeeded in bringing the price of aluminium down from £23 to 28*s*. a pound. The American, H. T. Castner, was contributing materially to the development of the chemical process when an entirely new phase in this industry began with the remarkable work of another American, Charles Martin Hall, of Oberlin, Ohio. In 1886 this inventor succeeded in producing electrolytic aluminium, his first experimental apparatus including a small graphite crucible, a plumber's blow-lamp, and some electric batteries improvised out of a number of jam jars. But it was the energy supplied by dynamo-electric machinery which made successful exploitation possible. As we noted in Book II., machinery for generating electricity was being rapidly evolved about this time, and among the many reactions of this development upon industry was a great reduction in the cost of producing aluminium by the electrolytic process. Apart from electrical considerations the important feature of Hall's process lay in using cryolite, a double fluoride of aluminium and sodium, and the fact that this material in a molten condition will take into solution a considerable quantity of alumina. The solution was submitted to electrolytic action at about 800° C., and it was found that so long as an electrical pressure of not more than 6 volts was used, the oxide of aluminium was split up into aluminium and oxygen. Incidentally, the cryolite solvent was unaffected by this treatment.

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[1] The metal is still called aluminum in the United States, not aluminium.

At about this time Alfred and Eugene Cowles, also of Ohio, were busy developing an electric furnace of the resistance type, the current not being used electrolytically, but solely to engender great heat. Yet another furnace was designed by a French inventor, Héroult, in 1886. This was similar in principle to Hall's in that it combined electrolytic action with electric furnace methods. Oxide of aluminium was placed in the furnace, the ore first being heated to a temperature at which it fuses. Then by electrolysis the aluminium was separated from the oxygen and the other constituents with which it is normally combined in the ore. In course of time the Hall and Héroult processes became practically indistinguishable, and are now adopted throughout the world for the production of aluminium.

Turning now to the full sequence of processes by which aluminium is produced from the ore at the present time, it should be explained in the first place that there are many variations of detail in the methods adopted. In what follows, therefore, we shall only summarise in a general way the procedure most widely followed. Aluminium occurs in nature in several forms, but so far only aluminium hydroxide has been exploited successfully for the production of the metal. Some day a method of getting aluminium out of china clay and other common substances in which it abounds may be discovered. This would enormously extend the possibilities of manufacture.

So far, however, all attempts to separate silica from the aluminium in clay have been unsuccessful. The hydroxide, which, as we have indicated, is the only present source of supply, is universally known as bauxite ; having first been discovered near Les Baux in the South of France. In appearance it is an earthy mineral varying in colour from white to red.

Open mining methods are commonly adopted for procuring the ore. Manufacture is dependent in the first place on the preparation of pure alumina, a considerable proportion of the whole cost of the finished product being due to the elaborate purification processes which are found necessary. First the ore is crushed, and if necessary, washed. The material is then submitted to calcination in a rotary kiln, destroying the organic matter, evaporating the moisture and converting the iron (which is usually found mingled with the ore) into ferric oxide. Subsequently the material is again crushed, this time to a finer mesh, and then stored in large silos. From the silos supplies are taken as required for further treatment in steam-jacketed vessels ; the alumina content being dissolved out of the bauxite by caustic soda. The alumina is then precipitated out by treatment with aluminium hydroxide, and submitted to a final calcination at a temperature of 1000° C. The water of hydration is driven off, and the alumina, in crystalline form, is then packed in bags for transport.

We may pause here a moment to explain why transport of the material at this stage is necessary. The explanation is quite simple. Aluminium cannot be produced from the alumina economically unless an ample supply of cheap electric power is available for operating the furnaces. Hydro-electric development has so far been found the most satisfactory way of meeting the heavy demands made by the aluminium industry, and as it so happens that water power and bauxite have seldom been found close together, the alumina must be shipped to the sources of power for final treatment. The Northern Aluminium Company of Canada may be cited as an example. This corporation, which controls the largest, and probably the best organised, aluminium plant in the world, obtains its supplies of bauxite from deposits sixty miles above Georgetown in

British Guiana ; whereas the water turbines, generators, and aluminium production works are situated on the Saguenay river in Canada. Some conception of the enormous amount of energy now used in the manufacture of aluminium may be obtained from the fact that the water turbines at this one factory have a capacity of approximately 800,000 horse-power.

The electric furnace consists of an oblong receptacle lined with a refractory material, within which there is a heavier lining of carbon forming the cathode. The current is introduced by means of thick carbon rods forming the anode. These dip into the molten mixture of alumina dissolved in cryolite, which is fused by the heat engendered. The metal when fused is just a little heavier than the other materials in the furnace. It is therefore able to sink to the bottom, where it accumulates on the cathode and is drawn off at intervals. This lowers the level of the molten contents, increasing the electrical resistance and causing a pilot lamp connected across the main terminals to light up. In this way the attendant is warned that more alumina must be supplied to the furnace.

It will be seen from this necessarily brief outline that aluminium is altogether the offspring of physical science as applied in its various branches—chemical, electrical and metallurgical. Rule-of-thumb methods, based on no matter how many centuries of practical experience, could never have led to the discovery of this wonderful metal. And to applied science we owe further the extraordinarily rapid progress which has been made in the production of aluminium. Just what progress has been made may be gauged to some extent from the fact that in 1890 the metal cost £1,085 a ton, whereas now the cost is approximately £95 a ton ; while in the same period the total annual output has increased from 40 tons to nearly 250,000 tons.

It would require a whole book to deal at all adequately with the many uses to which aluminium is now put, and the many new industrial developments which it has made possible. The reader will be aware that aluminium may be used alone, or alloyed with other metals. To aluminium and its alloys we owe much of the progress made in the automobile industry, while without them the modern aeroplane and airship would be impossible. The automobile engineer, and later the designer of aircraft, sought constantly for materials lighter and stronger than anything known before, seizing with avidity upon aluminium as a substitute for cast iron and—as, for example, in the case of the rear wheels of the London General Omnibus Company's vehicles—even for cast steel. Crank-cases, gear boxes, dashboards and even bodywork are now made of the new metal. Quite apart from the advantage conferred by its light weight, the high thermal conductivity of aluminium has led to its use for the manufacture of cylinders and pistons ; a subject upon which we had occasion to comment when discussing internal combustion engines in Book II. And now the use of aluminium for automobile bodywork has led to the adoption of this metal for the panelling and ceilings of railway passenger coaches. As for the monster airships which have been built in recent years, it is of interest to record that the huge latticed framework which is such a striking feature of their construction, is made almost entirely of aluminium alloys.

In the chemical and allied industries, in breweries, jam-making factories, sugar refineries, and a host of other enterprises, the general cleanliness of aluminium and the facility with which it can be built up by autogenous welding into huge, one-piece vessels, has led to its use to an ever-increasing extent. Similarly, aluminium has invaded that miniature chemical works, the domestic kitchen, and will no doubt do so more and more in the future. Here again its light weight, its natural cleanliness, and its high thermal conductivity all tell in its favour.

It is, perhaps, not generally realised that aluminium is now being used increasingly in the electrical industry, particularly as a conducting material on switchboards and for overhead transmission lines. There are already thousands of miles of aluminium cable distributing electricity, the conductors of some of the longest transmission systems in the world being made entirely of aluminium. Finally, to bring to a close a list of uses which would otherwise threaten to lengthen this section indefinitely, aluminium is used for the production of intense heat for welding and other purposes. A material known as

(*Courtesy of the B.C.G.A.*

Pouring molten aluminium for a motor-cycle crank-case.
The metal is melted in gas-fired furnaces.

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" thermit " is made of finely powdered aluminium mixed with iron oxide. This mixture is placed in a crucible and ignited. Combustion continues rapidly throughout the whole mass, the temperature rises to about 5,500° F. within thirty seconds, the iron runs down to the bottom of the crucible in a molten state, while the aluminium—which has great affinity for oxygen—floats on top in the form of aluminium oxide. The molten iron is run off as required for welding rails, repairing fractured parts of machinery and such-like industrial requirements. Professor H. T. Barnes has further added to the range of uses to which aluminium may be put by demonstrating the effectiveness of thermit for breaking up ice jams and dispersing icebergs.

3

Lead and Tin

Turning next to lead and tin, we come once more to metals which have been utilised by man from very early times.

Lead was not used to any marked extent in ancient Egypt, although lead ores occur in that country. It had become fairly common by the Eighteenth Dynasty, however, when among other uses it was employed for weighting fishing nets. As with iron and copper, Asia Minor was one of the earliest centres of lead mining, and the metal was already a common article of merchandise among the traders of Cappadocia by the close of the third millennium B.C. By the end of the second millennium the Assyrians were using stamped lumps of lead as currency, while there is evidence pointing to the existence of lead coins as early as the time of Sennacherib.

Various references to lead occur in the Old Testament,[1] and Homer mentions it in the *Iliad*.[2] In the 5th century B.C. the Greeks exploited their ores extensively, at one time employing over 20,000 slaves in their mines at Laureion, where silver and lead were found together—as, indeed, not infrequently happens. The Romans, too, mined lead and used it for making water pipes and for many other purposes. During the Empire considerable quantities were exported to the East, where it was used for native coinages. In those days the finest lead came from Spain, though the Romans also procured considerable quantities from Britain and other parts of the Empire. It is interesting to note that Vitruvius criticised the use of lead for water pipes as being unwholesome. In support of his view he referred to the unnatural pallor of lead smelters, attributing their appearance to the fumes given off when lead is smelted.[3]

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[1] See Cruden's *Concordance*.

[2] *Iliad*, XXIV, 109.

There are few metallurgical operations so simple as the production of metallic lead from the ore. At its crudest the process involves little more than roasting the broken ore by piling it on top of fuel placed on the ground. The metal fuses at 325° C., and runs out at the bottom of the heap. Already in the days of ancient Greece, however, roasting was preceded by crushing, grinding and other concentration processes. Coming down to the time of Agricola, ores in general were "sorted, broken with hammers, burnt, crushed with stamps, ground into powder, sifted, washed, roasted and calcined." The ore was roasted, he explains, either to soften it for crushing preparatory to smelting, or in order to consume the impurities mingled with the metal.

The form of ore most widely distributed in nature is sulphide of lead, or galena. Mining commonly involves underground operations. At the Kingdon mine in Ontario, for example, a vertical depth of 1,150 feet has been reached, and levels established 125 feet apart, the longest being 2,500 feet. It is scarcely necessary to describe in detail the furnaces and other plant used for treating the ore, as these present few features of interest distinguishing them from those referred to in previous sections. Concentration is now generally carried out by the flotation process. The sulphide may be roasted in reverberatory or blast furnaces, some of it being resolved into lead sulphate and some into lead oxide ; part of the sulphur being burnt off as sulphur dioxide. On further heating the two compounds of lead react with the unaltered ore, yielding metallic lead.

The separation of silver and lead involves special treatment.

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[3] *Ten Books on Architecture*, Book VIII, Chapter VI.

A considerable amount of material relating to tin mining and smelting in Britain as carried out from the 12th century A.D. onwards has been collected by Mr. G. R. Lewis in his book on *The Stanneries* (published as Volume III. of *Harvard Economic Studies*), but for our present purposes it will suffice if we refer once more to Agricola's work, *De Re Metallica*. Here we are informed that the metalliferous material was sometimes found not very deep beneath the surface of the earth, but sometimes so deep that it was necessary to drive tunnels and sink shafts. The material was transported to washing boxes in wheelbarrows. Here much of the worthless material was sluiced away. The valuable portion was then roasted in a furnace resembling an oven, where it was stirred up and levelled down again repeatedly, removing some of the volatile impurities and oxidising others. The tin was then smelted out of the ore (or tinstone) in a furnace arranged so that only a moderate heat could be obtained, " for if the fire were fiercer, tin could not be melted out from the tinstone, as it would be consumed and turned into ashes."

Modern methods of tin mining and smelting, like those adopted in the production of lead, present few novel features. The ore is found in veins or lodes in the rock, or scattered in alluvial deposits. Tin occuring in lodes involves the use of explosives, owing to the very hard nature of the gangue. The material is broken and powdered by modern equivalents of Agricola's rude breakers and stamps, after which it is washed, calcined, and washed again to ensure concentration. It is then fused in a furnace and subsequently refined by cautious heating on an inclined hearth, the purer tin running off and being further purified by stirring or " poling," as it is called. This liberates the oxygen diffused through the metal as oxide.

The methods of alluvial tin mining vary according to local conditions. Sluicing with a hose, open-mine working, underground working, and dredging are adopted in one part of the world or another. In dredging mining a pontoon is floated on a pond specially constructed to receive it. At the front of the pontoon an endless chain of buckets raises stanniferous soil from the working face at the bottom of the pond to the interior of the vessel, where it is washed and screened. The tinstone is retained and the refuse separated from it is deposited at the rear. The pontoon is worked slowly forward into the mining field, carrying its pond with it. The whole process is simply a large-scale elaboration of the primitive methods used by the natives in Malaya and elsewhere, who dig out small quantities of tin-bearing soil and wash it in a pan. The refuse is swilled away, while the heavy tinstone is left behind in the pan.

Just how remarkably the production of tin has been increased in recent years by the substitution of machinery for muscle may be indicated by quoting figures for 1900 and 1928, world output in those two years being 75,000 tons, and 170,000 tons.

Tin has a variety of industrial uses, including the manufacture of tinfoil for silvering mirrors and for wrapping chocolate and tobacco. It also enters into the composition of various alloys, including brasses, bronzes, pewter, and solder. Principally, however, it is used for coating sheet steel in the manufacture of "tinplate," already referred to in Chapter III. of this Book. Tins for biscuits, cakes, tobacco, cigarettes, sweets, and an ever-increasing quantity and diversity of preserved foods are made out of tinplate. Indeed, so large a proportion of the world's food supply now depends on ample supplies of tin that we may well pause to inquire whether there is danger of demand exceeding supply ; and if so, whether there is any probability of an effective substitute for tin being found.

So far as future supplies are concerned, it is highly significant to note, first, that more than half the world's total output has in recent years come from a metalliferous belt stretching from Burma to the Dutch East Indies ; and in the second place that according to more than one authority the bulk of the rich alluvial deposits in this region will have been exhausted by 1950 or even earlier. Having regard to this possibility, and the likelihood that the demand for tin will for a while continue to increase, it will be seen that the prospect is far from satisfactory so far as supplies of this particular metal are concerned. Fortunately, although no substitute has yet seriously threatened the supremacy of tinplate as a material for making food containers, several other metals have been experimented with and are giving highly promising results. Stainless steel containers, for example, are less liable to corrosion than tinplate, and are highly commended by all the authorities who have made a special study of this matter. The main objections to such containers are relatively high cost of manufacture, and dull appearance compared with tinplate. Nevertheless, it can hardly be doubted that the cost of stainless steel will be materially reduced as processes of manufacture are perfected. Another substitute which may eventually become a serious competitor with tinplate is aluminium. Here also price is an obstacle, but here again it is safe to anticipate that in course of time cost of production will be reduced. Soldering also presents a difficulty in the case of aluminium. It is stated, however, that as a result of intensive research a solution of this difficulty may be anticipated at an early date.

Still another possibility is aluminium-plated steel. A German firm has recently announced that it will shortly market a sheet steel electrolytically plated with aluminium, at a price 20 per cent. lower than the current price of tinplate, though it may be doubted whether aluminium-plated steel would be suitable for such a wide range of uses as tinplate has shown itself to be. Finally, we may note that various lacquers have been experimented with, and their suitability as substitutes for tin has been demonstrated, but only for particular products. No lacquer has yet been discovered which is universally suitable for coating food containers.

Summing up, it is reasonably safe to say that either because of rising tin prices, due to increasing scarcity, or because substitutes will have been improved and their production cheapened, or for both these reasons together, the problem of the preserved food supply will ultimately be solved by the widespread adoption of some material other than tin for coating food containers.

4

Non-Ferrous Alloys

We have now discussed the more important of those metals which are used in large quantities. There are many others which are not used so abundantly. The processes involved in their extraction need not be reviewed here, as we have already sufficiently indicated the nature of such processes in general, and are not concerned to stress the extent to which they vary in minor details.

There remain the non-ferrous alloys. These are so numerous and their number so constantly increases, that we can only deal with them briefly, and in the most general terms.

Those who have had little practical experience in the manipulation and treatment of materials sometimes express surprise that non-ferrous metals and their alloys are used at all. Seeing what a wide range of requirements can be met by steel, steel alloys, and cast iron, most other metals may appear at first sight to be superfluous, or at least of diminishing importance in modern industry. This, however, is not so. Non-ferrous metals are, in the first place, more suited than steel to the manufacture of castings, doubtlessly owing in part to their much lower melting range. Again, though in general the non-ferrous metals and their alloys possess lower tensile strength, and are less hard than steel, these very defects are advantages from the point of view of ease in manipulation ; particularly where cutting and other machining operations are concerned. It must also be noted that inferiority in strength and hardness is not seldom accompanied by superior ductility and toughness, and these are qualities of particular value where materials are shaped by spinning or pressing processes. Then the non-ferrous metals can usually be worked while cold—a quality which on occasion is of considerable value. Other valuable properties which distinguish some at least of the non-ferrous metals or their alloys are superior resistance to corrosion, light weight, superior electrical and thermal conductivity, the power of reducing friction, and finally the quality which makes brazing and soldering possible, processes which of course are quite outside the scope of the ferrous metals.

Of all non-ferrous alloys, those containing copper are the most widely used, as well as being the earliest known to mankind. For thousands of years man has been experimenting with and using alloys of copper and tin. But at the risk of wearying the reader by repeated emphasis, it is necessary once more to point out that, apart from the researches of a few pioneers, only during the past thirty or forty years has man obtained any comprehensive knowledge of the constitution and behaviour of metals in general, and alloys of metals in particular. The ancients recognised seven metals and knew at most two or three alloys. To-day the metallurgist knows some fifty metals, while scarcely a day passes without adding to the number of alloys which have been produced. The alloys of copper, for example, now comprise mixtures of copper with zinc, tin, iron, manganese, aluminium and other metals, either singly or in any of a large number of combinations.

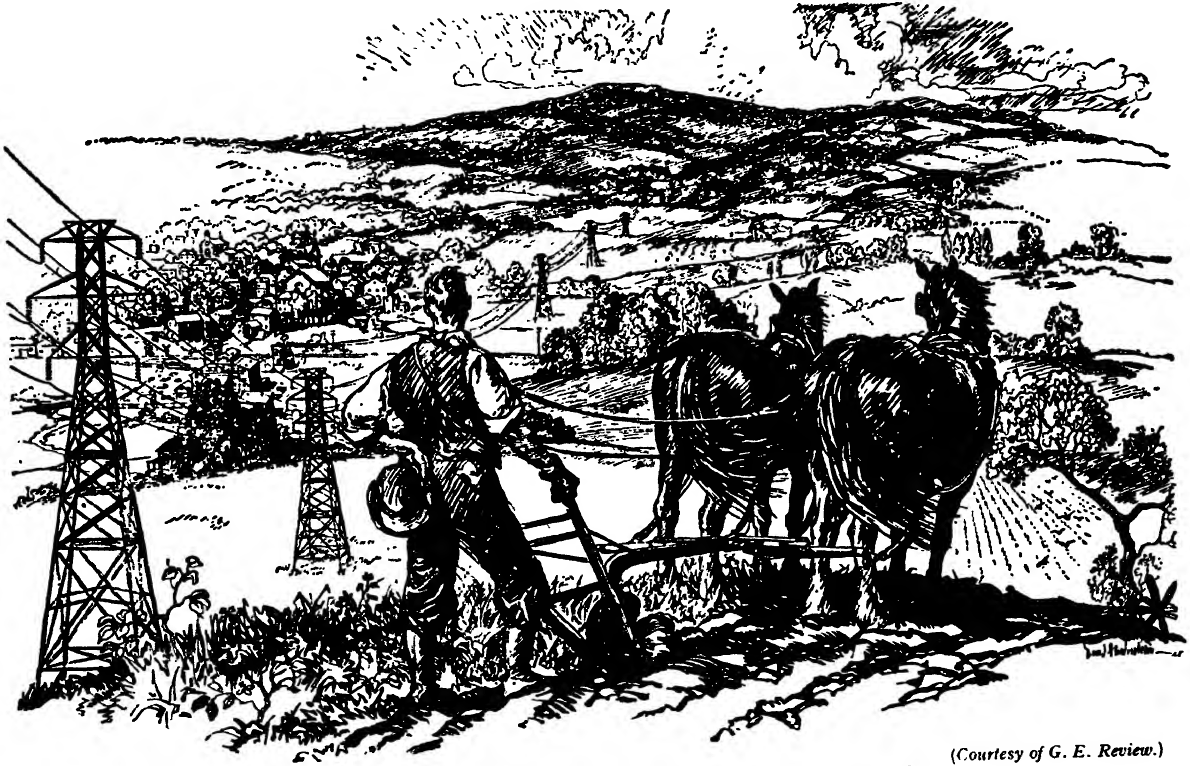
It is found that the best results are usually obtained from an alloy of two selected metals when they are mixed in approximately definite proportions. Any marked variation in the proportions is likely to produce quite different and, usually, less satisfactory results. This had long been known empirically in relation to a limited range of alloys, but little progress was made towards enunciating satisfactory theories in explanation of observed facts until Matthiessen, in 1860, stated that alloys must be regarded as solidified solutions. Since then this view has been made the basis of a vast amount of investigation into the constitution and behaviour of alloys. It has been shown, for example, that solutions of metals may be considered as having freezing points just like ordinary aqueous solutions of salts, with which—so far as freezing is concerned—their behaviour is analogous. With the aid of pyrometers the cooling and freezing of alloys can now be followed with great accuracy ; the constitutional changes which occur in an alloy at the moment of freezing or melting, or at other temperatures, can be detected by noting changes in its physical properties, indicated by the evolution or absorption of latent heat ; while observations and records and the deductions made from them can be checked by microscopic examination of the structure of the alloy after its characteristics are once fixed. Finally, it is possible to follow with X-rays the changes in spacing and orientation of atoms due to the union of two or more metals, to variations in the proportions in which metals are united, and to the heat treatment to which the alloy may have been submitted. The knowledge gained by these means, together with the much more effective control over all processes which can now be exercised, ensures results in the production of special alloys to meet special needs which would have been quite impossible only a few years ago.

Of the newer products of modern metallurgical science few have aroused more widespread interest than a wrought aluminium alloy called "duralumin," which, as already stated, consists of aluminium with small additions of copper, magnesium, silicon, manganese, and iron. The iron content is so small that though not strictly a non-ferrous alloy, duralumin may be classed as such here. The first step in the evolution of this remarkable alloy involved adding copper and zinc to aluminium. The early alloys thus formed showed a considerable increase in strength over aluminium by itself. Such alloys were always used in the cast condition, however, and, unfortunately, aluminium alloy castings are very brittle. The production of alloys such as duralumin, which can be forged, has opened up an entirely new vista of possible uses for aluminium. It was found that duralumin could be heat treated, resulting in a distinct improvement in its mechanical properties. This treatment involves heating, quenching, and tempering. It is noteworthy, however, that the material is not hardened by quenching, a procedure which only puts it into a condition such that subsequent tempering hardens it and increases its strength. After tempering the properties gradually improve ; duralumin spontaneously hardening by itself at ordinary temperatures over a period of about seven days.

Among other non-ferrous metals of the greatest interest we may mention those the composition of which includes nickel.

Most of the progress which has been made with nickel alloys is a post-war development, though the commercial exploitation of nickel-steels began about 1890 ; while nickel-copper alloys appear to have been known for at least 2,000 years. The increase in toughness, strength, and hardness produced by making nickel a constituent of alloys is surprising, and has led to extensive use of nickel steel for automobile manufacture, mining and excavating machinery, machine tool parts, steam turbine rotors and speed-reducing gear, and a host of other industrial purposes. But here we are concerned with non-ferrous alloys of nickel, among which we may include Monel metal, although this, like duralumin, includes a minute quantity of iron. The primary constituents of Monel metal are nickel, copper, silicon, and manganese. It has considerable capacity for resisting corrosion, also erosion by water and steam, and takes and retains a bright nickel finish. Nickel-copper alloys have many uses. One known as " constantan " is used as an element in the construction of thermo-couple pyrometers and also as electrical-resistance wire. Another alloy called cupro-nickel has been widely used for making condenser tubes. A nickel-manganese alloy is used for spark-plug terminals ; the properties of value for this purpose being resistance to oxidation and alteration at temperatures up to 1,100° C., a high electrical resistivity, and a marked thermal electro-motive force against iron or copper. Nickel-chromium alloys are valuable for their ability to withstand high temperatures, and are much used for furnaces, annealing boxes, lead, cyanide, and salt pots, retorts and many similar industrial purposes. They have an important advantage over cast steel in the more rapid penetration of heat through their thinner sections, rendered possible by greater resistance to oxidation and relatively high strength at high temperature.

So we might continue, making a catalogue not only of the properties of non-ferrous nickel alloys but of all other non-ferrous alloys as well. Such a list would, however, be outside our present scope. In this part of our book we have endeavoured to follow the main current, the general trend of metallurgical progress ; and though we have not hesitated to give particulars of general industrial applications when these appeared to be of special interest, our primary purpose has been to put before the reader the broad facts, rather than a mass of bewildering detail, bearing on power-plant evolution.



(Courtesy of G. E. Review.)

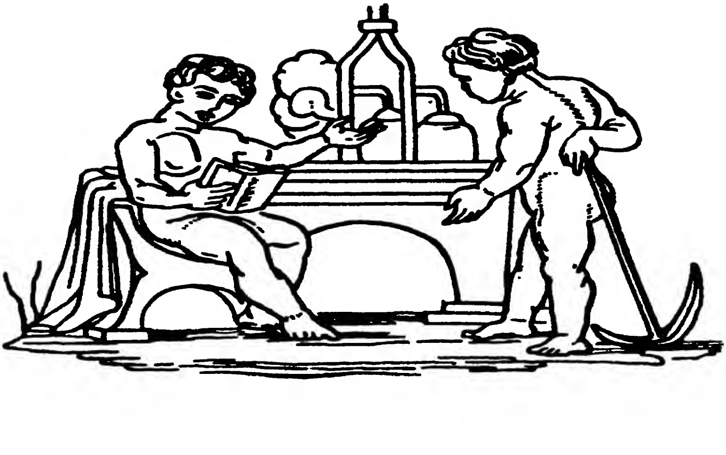
“ The old order changeth, yielding place to new.”

EPILOGUE

WORLD POWER

“ More gardens will they win than any lost ;
The vile plucked out of them, the unlovely slain.
Not forfeiting the beast with which they are crossed,
To stature of the Gods will they attain.”

George Meredith.



EPILOGUE

WORLD POWER

I

World Power Conferences

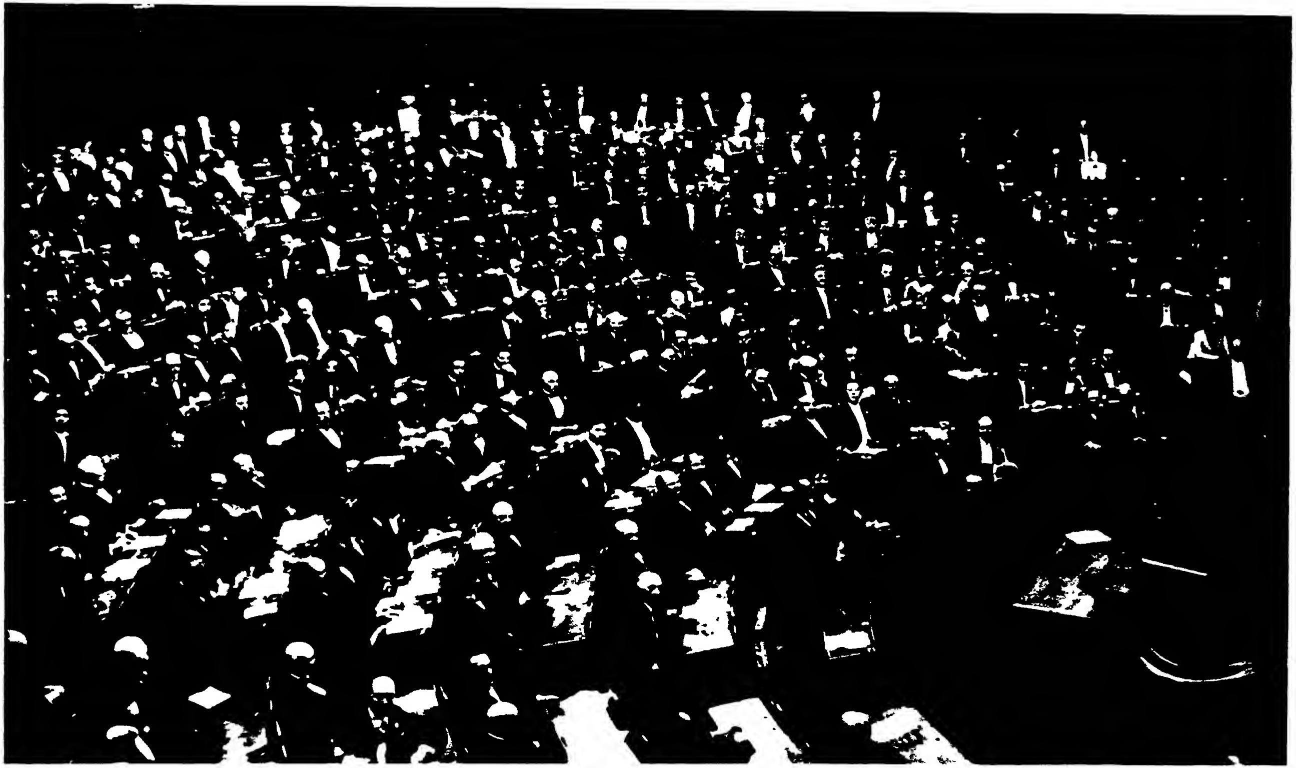
Our survey now nears its close, but the quest for power goes on. For good or ill it will assuredly go on so long as the human race endures.

Far-reaching developments in the production, distribution, and application of power are taking place even as we write. Such developments no longer merely effect a change here and there, and now and then, in our ways of living. They influence every sphere of human activity, including the quest for power itself. It is continuous change, swift and sweeping, that our progressive control of Nature's forces has brought upon us ; creating entirely novel problems, making ceaseless adjustment necessary throughout the social structure, and even bringing fresh perplexities to those who live in cloistered seclusion far from the dust and heat of everyday industrial affairs. And as there is no prospect whatever of controlling change on this scale except by world-wide co-operative effort, it is fitting that we should make some reference here to the World Power Conferences, and the work of international co-ordination of power engineering science and practice which they have already taken in hand.

Prior to the Great War each nation endeavoured to solve its own power problems with little reference to methods adopted in other parts of the world. Views were interchanged from time to time, each nation benefited to some extent by the progress of others, and, as might be expected, similar problems were not infrequently solved on similar lines. But there was no comprehensive attempt to co-ordinate and standardise ; to co-operate internationally in establishing a clearing house for the ideas of all peoples ; to systematise the application of power engineering knowledge to the needs of the whole human race. But after the war came wider vision. Thoughtful men began to realise that an end must be made of the old, haphazard methods of exploiting and utilising world resources in materials and power. This realisation was not confined to any one nation. But the initial steps towards international unification were taken in Great Britain, leading to the opening of the First World Power Conference in 1924.

This Conference was made possible, in the first place, by the Council of the British Electrical and Allied Manufacturers' Association, which ensured the necessary financial support. Prestige was added by the fact that leading scientists, engineers, and industrialists in Britain agreed to associate their names with the work. The Government of the day also gave its support, after which engineers from other countries were invited to meet in London to survey the power resources of the world. The United States, France, Italy, Japan, and other great nations agreed to send representatives, and eventually Germany was also asked to participate. Thus the Conference came into being, and was opened by H.R.H. the Prince of Wales in the presence of about 2,000 delegates from over forty countries. Of its manifold activities the man in the street knows little ; yet its initiation and successful consummation were among the most momentous events of this, or indeed, of any age. To the men of vision who first realised the possibilities of such a conference, and then by unremitting effort made their dreams come true, mankind must ever owe a great debt of gratitude. They gave evidence of a real statesmanship such as is unhappily only too frequently lacking in the political world to-day.

The Proceedings of the First World Power Conference fill four large volumes, a fifth containing an index. Volume I. deals with various aspects of world power resources, available and utilised. Volume II. discusses water-power production, the preparation of fuels, and steam-power production. The third volume contains papers on internal combustion engines, gas and fuel, power from other sources, power transmission and



(Courtesy of "World Power.")

Delegates at the Second World Power Conference, Berlin, 1930.

To face p. 333.

distribution, standardisation and research, and illumination. Volume IV. is concerned with power applied to industrial and domestic uses, power in electro-chemistry and electro-metallurgy, also power for transport, economic aspects of power resources, and education, health, and publicity.

The Second World Power Conference, recently held in Berlin, was officially opened on June 16, and closed on June 25, 1930. Nearly 3,500 members from forty-eight countries attended the meetings—nations being represented, quite literally, " from China to Peru." It is interesting to record that Dr. von Miller, the Honorary President, can claim to have been one of the very early pioneers in electrical transmission, having established the first long-distance line from Lauffen to Frankfort. We cannot yet attempt to assess the value of the work done at the Berlin meetings, but it may be pointed out that the essential utility of these Conferences lies not so much in immediate detailed accomplishment, great as this undoubtedly is, as in the evidence they afford of the limitless gains to be secured by future work on lines similar to those already laid down.

An important aspect of the Berlin Conference has been commented upon in a recent issue of *Mechanical Engineering*, the monthly journal published by the American Society of Mechanical Engineers. The remarks there made are worth quoting at some length :

> " This international gathering of engineers and economists is not a peace or disarmament conference. It concerns mechanical power that in the last two hundred years, and particularly in the last fifty years, has performed much of man's work for him, has increased his productivity, and has emancipated him from the oppressive burden of physical labour. It is this power that has created an industrial civilisation, in which, because of their novelty and apparent desirability, and because they are so readily produced, things have received more attention than values.
>
> " There are three broad aspects in which problems of industrial power are discussed. Engineers confine themselves, as a rule, to the technological aspects of power. Here is a structure of hard fact which suits the nature of engineers. It towers starkly without sign of sentiment and emotion, and almost devoid of the prejudices of personal opinion. The second aspect is the economic one in

which engineers take an increasing interest. But here, because they find fewer facts, wider influences, and more subtle implications, they seldom consider more than the well-known economics of commerce. To the third aspect of power engineers pay scant heed. Perhaps it is not on them that social problems should be laid. Perhaps they prefer to remain the instruments by which some greater craftsman may fashion civilisation to human needs and ideals."

Now it is our view that engineers will be compelled, by force of circumstance, not only to take more and more interest in power economics, but also in the reactions of power development upon the whole fabric of civilisation. It is *their* work which is adding so extensively to the complexity of social relationships ; it is, we hold, *their* manifest duty to help solve the social problems which now confront mankind. And, after all, who is more likely to approach such problems with understanding, and provide the necessary energy to ensure their satisfactory solution ? Though no doubt they have their share of the faults common to men in other professions, they have also the incalculable advantage of living from their youth up in a world, not of make-believe, but of things as they really are. For engineers are primarily concerned with facts. Their work is based on science ; it is rooted in reality. It is, moreover, creative work ; work, that is, especially fitting them to take thought for the world of to-morrow which is ceaselessly developing out of the world of to-day.

Yet not engineers only, but all thinking men, of all professions and occupations, must needs participate in this work of social reconstruction. And so that these others may participate intelligently, it is essential that they should have access to general surveys of engineering progress, which explain in the simplest possible terms just what engineers are doing and why they are doing it. Such surveys should be made and continually revised by men with a wide knowledge of engineering theory and practice, and a special gift for lucid interpretation and exposition ; men able to compile intelligible and interesting summaries for the general reader. It was with the need for such summaries in mind (though with no illusion that we were particularly well equipped for the task) that we undertook to write this book, *The Quest for Power.* The time will come, perhaps, when work of this nature will be regarded as being by no means the least important of tasks undertaken—as a matter of course—by successive World Power Conferences.

2

Possibilities of the Future

It is no part of our purpose to attempt an elaborate forecast of further power developments. But having discussed man's past and present achievements in controlling the forces of Nature, we may appropriately add a few notes on some of the power possibilities of the future being discussed, more or less seriously, by engineers and men of science at the present time.

Among such possibilities the gas turbine occupies a prominent position. It promises to effect a complete revolution in the production of power from coal and oil—that is when success is attained. But though an enormous amount of thought and experiment has been applied to the development of a practicable gas turbine, results so far have been meagre. We have seen in Book II. that exhaust gas turbines, utilising the energy remaining in the exhaust gases of reciprocating engines, are a *fait accompli.* The temperatures in a true gas turbine, however, must necessarily be much higher, and suitable materials are not yet available. Nevertheless, it seems only a question of time before a practical solution is found of the difficulties which have to be faced in this regard.

The mercury vapour turbine, improvements in the design of the electric accumulator, more extensive and effective use of heat now wasted, including the development and use of more efficient heat accumulators, are but a few of the lines along which research is being carried out at the present time, and is likely to be carried out more intensively in the future. Wireless transmission of power, and the production of entirely new materials synthetically to meet specific requirements, must also be mentioned as possibilities ahead of us. Again, thought and experiment are being devoted to methods of tapping external power at points nearer the one great source—that is, the energy radiated from the sun. We say the one great source, for direct access to and control of energy now locked up in the atom is for the present outside the limits of practical speculation.

Schemes for directly utilising solar heat include plants in which the sun's radiant energy is focussed on boilers by means of parabolic reflectors ; also plants without mirrors in which the sun's rays fall directly on heat-absorbing material in long shallow vessels, thermally insulated at the sides and bottoms ; and covered by layers of glass with an air space between, which prevents re-radiation of the heat falling on the vessel. Water, or some other suitable fluid, flows through the trays and conducts the heat to a storage tank, flowing thence to a tubular boiler containing another fluid—such as sulphur dioxide—which being vaporised is employed to operate a small steam turbine or engine. Another scheme for the direct use of solar heat is based on the fact that water will boil in a rarefied atmosphere at a low temperature, and involves taking advantage of the temperature difference between the heated water or air at the surface of the ocean and the cold water down below. The latest proposal on these lines, discussed at the Second World Power Conference, is to utilise the temperature difference between the winter air in the Arctic and that of the water under the ice sheet. The suggestion made is that in this way power should be developed in turbines in which the working substance would be a hydrocarbon of low boiling point, such as propane or butane, evaporated by the heat in the sea water and condensed by a brine solution at minus 22° C.

A different scheme, but one which may be considered as being in much the same category, is to run sea water from the Mediterranean into a great depression in the Libyan desert. This depression, the Qattara Depression, has an area of some 7,000 square miles at sea level, and a maximum depth of about 400 feet below that level. It has been calculated that over 40,000,000 tons of sea water a day could be allowed to flow into this depression continuously, the water being also continuously evaporated by the heat of the sun at the same rate when exposed in the inland sea which would be formed.

Dr. John Ball, Director of Desert Surveys of Egypt, states that a continuous effective output of 160,000 horse power could be obtained from water turbines installed in connection with this project.

Turning now to prospects of utilising the internal heat of the earth, schemes are already either under discussion or actually in hand to tap the heat from volcanoes ; from geysers and hot springs ; and also to bore down through the earth's crust to whatever depth may be necessary to obtain the required temperature. As long ago as 1904 the feasibility and cost of such boreholes was discussed by Sir Charles Parsons in his Presidential Address to the British Association. In general, the idea would be to sink two boreholes, and having connected them by boring a reservoir at their base, to pump water down one and up another borehole, the water thus heated being then available for power purposes. A depth of about two miles would be necessary to obtain a temperature equal to water boiling point at atmospheric pressure.

The use of tidal power is a possibility of the more immediate future. Wheels turned by the ebb and flow of tidal water have been used for centuries, probably having been first adopted long before Domesday was compiled, though we have no definite evidence on this point. Smeaton installed such wheels beneath Old London Bridge. These were used for pumping, the wheels being mounted on floats, and turning one way as the tide rose and the other as it fell. But water wheels of that type have no future, modern projects being concerned with the building of barrages across tidal rivers, such as the Severn and Dee in Great Britain, thereby impounding water which could be allowed to flow out again through water turbines. The amount of power to be developed depends primarily upon the head, and quantity of water in unit time, available ; Great Britain being exceptionally well favoured by its tidal range and suitability of many of its estuaries for the adoption of this type of power project. It is probable, however, that the most attractive—and at the same time most daring—suggestion yet made is to build a barrage across the inner extremity of the Bay of Fundy, which has a tidal range of 40 feet. Professor A. H. Gibson has stated that "the headlands at its outlet are less than three miles apart, and it is safe to say that through this narrow gap energy, equivalent to more than 100,000,000 horse power hours, runs to waste during the ebb and flow of each tide. To utilise this would require an engineering feat more tremendous than anything yet attempted by man, but in years to come the game may be worth the candle."[1]

Other possibilities of the future are a revival of the use of wind power, and the harnessing of atmospheric electricity. The latter cannot be said to be of more than academic interest at the present time. But there has been some investigation made in recent years into the improvement of existing designs of windmills, particularly in Holland and Denmark. In Great Britain experiments have been carried out with stream-line vanes incorporating the knowledge gained in the design and use of aeroplane propellers. It must be recorded, however, that difficulties have been experienced in regard to cost of both manufacture and maintenance. Moreover, most of the old disadvantages inherent in the development of wind power still have to be contended with ; nor is it at all clear how they are to be circumvented. The windmill with (approximately) vertical sails and horizontal axle is of necessity extremely limited in output. The ordinary old-fashioned Dutch type of mill, for example, with four sails each 24 feet long and 6 feet wide, only generates about 4·5 brake horse-power in a twenty-mile wind. Even supposing that the efficiency of such a mill could be increased rather more than threefold, so that when driving an electric generator an output of 10 kilowatts was obtained, some 16,000 of such windmills would be required to equal the output of the giant steam turbine installed at Hell Gate Power Station, New York City, referred to in Book II. And the construction of larger units is rendered difficult by the fact that the sail area of a wind-wheel increases with the *square* of the diameter. Mr. Robert S. Ball, in his book *Natural Sources of Power*, points out that :

> "By increasing the size of the wheel its weight must be enormously

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[1] A. H. Gibson, *Natural Sources of Energy*.

increased to provide strength to withstand the increased wind pressure. If all the linear dimensions of a wheel were doubled its weight would be eight times the original, but at the same time the sail surface would be only four times as great. Consequently there is a limit to the size above which the wheel becomes so heavy that for light winds it is useless."

Taking these facts into consideration, also the difficulties due to uncertainty and irregularity of working, among which must be mentioned the necessity of using electric accumulators or other means to compensate for such irregularity, it will be seen that there is little prospect of developing power on an extensive scale by any known type of windmill with sails moving in a vertical plane. It may be added that attempts to develop an efficient horizontal windmill, on lines not unlike those of the primitive Oriental windmills mentioned in Book II., but embodying modern engineering principles, have also so far met with little success. We have dwelt on this matter at some length, as, although wind power may very well be a possibility of the future, the difficulties to be contended with in developing an efficient wind motor are seldom sufficiently stressed in books written for the general reader.[1]

Finally we may turn to a brief consideration of the future of fuels and their utilisation.

It is fairly safe to assume that, with much waste eliminated, and with the development of other sources of power, the demand for coal is not likely to increase as time passes, and may actually decline. Indeed there is already a tendency for world consumption of coal to decline. In a summary of world-power resources recently issued at the instance of the Executive Committee of the World Power Conference, this is attributed partly to greater economy in use, partly to higher efficiency of power-generating and power-consuming plant, and partly to the wider use of substitutes for coal fuel, such as oil, and water power.

The more extensive exploitation of brown coal, peat, and shale deposits is largely dependent upon coal and oil prices. Under present circumstances there is no very marked tendency to increase the consumption of the lower grades of fossil fuels ; but as the cost of winning coal and oil increases, so will more and more attention be given not only to the other fossil fuels but also to vegetation and, it may be, fuels derived synthetically from the air as alternative sources of power.

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[1] One of the most ingenious of new wind power developments is the " S-rotor," a power wheel invented by the late Dr. S. J. Savonius, of Helsingfors, Finland. The S-rotor, which has a relatively high efficiency, can also be arranged to operate with water currents.

Such in brief outline are a few of the possibilities of extending man's dominion over the forces of Nature. Whether this extension will prove to be a blessing or a curse depends very largely upon the extent to which the dark and disturbing forces of *human* nature are also brought under control. Though the importance to mankind of power-driven machinery can hardly be over-stressed, we must not forget that, after all, the abiding problems of life are not technical, but moral. Machinery and the forces harnessed to drive it are in themselves neither good nor evil, though they have increased our potentialities for good and evil beyond measure. In so far as they have increased our potentialities for evil, we would say with Francis Bacon : " Let none be alarmed at the objection of the arts and sciences being depraved to malevolent or luxurious purposes and the like, for the same can be said of every worldly good ; talent, courage, strength, beauty, riches, light itself." And, on the other hand, we believe that once men allow good and wisdom—the God in their hearts and minds—to prevail, the quest for power will bring blessings in its train such as in our most sanguine moments we have seldom dreamed of or ventured to desire.

With the advent of power, and its promise of material plenty for all, there has dawned a new hope in the heart of man that at long last he may escape to wider horizons ; that the manacles of uncongenial toil, the iron of which has entered his soul, may be struck off or at least rendered so light that they no longer irk him ; that he may know the old, circumscribed and low-vaulted life no more ; that he may go on his way rejoicing, glad and lightsome as was Christian when his burden was loosed and fell from off his back. Not, indeed, that material plenty can directly effect so desirable a consummation, for

" a man's life consisteth not in the abundance of the things which he possesseth " ; but indirectly it will make this release possible, through a widening margin of leisure in which to contemplate first and last things, and to acquire the spirituality of mind which we are told " is life and peace." If it is legitimate to believe, as we do emphatically believe, that " the best is yet to be," then we may look forward with confidence to a future in which manual labour will dwindle almost to vanishing point ; a future in which power-driven machinery will be considered not only as beautiful as any other product of man's creative abilities, but as being the instrument of Him who said : " I came that they might have life, and that they might have it more abundantly."

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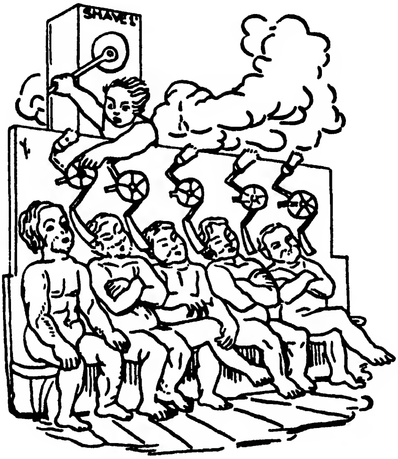ZIMMERN, Alfred, 66
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